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Estimating Mobile Source Pollutants in Microscale Exposure Situations

Southwest Research Inst.
San Antonio, TX

Prepared for

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Emission Control Technology Division
2565 Plymouth Road
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16. ABSTRACT

The goal of this study was to provide a method of estimating the concentration of any vehicle generated pollutant in areas where people are in close proximity to vehicles (microscale exposure situations). A list of common exposure situations was extracted from several hypothetical daily activity routines. These situations were: residential garages, parking garages, tunnels, street canyons and expressways. For each of the situations an appropriate dispersion model was selected from the literature for use in obtaining pollutant concentrations. To determine the exposure level for each case, the pollutant concentrations were calculated for typical and severe actual situations. The range of physical variables for each type of situation was obtained from a search of the literature, to define the typical and severe cases for each situation. Using the physical variables describing the typical and severe cases, actual locations were chosen to represent the typical and severe exposure for each situation. Pollutant concentrations were calculated for these actual locations using the chosen dispersion models. Concentrations were calculated using one gram per mile for tunnel, street canyon, and expressway situations, and one gram per minute for residential and parking garages. To use the calculated concentrations with emission factors other than one gram per mile or one gram per minute, the concentrations given in the report are multiplied by the desired emission factor in the correct units.

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Estimating Mobile Source Pollutants in Microscale Exposure Situations

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FOREWORD

This project was conducted for the U.S. Environmental Protection Agency by the Department of Emissions Research of Southwest Research Institute. The project was begun in January, 1980, and completed in February, 1981. The project was conducted under Task Specification No. 1 of Contract 68-03-2884 and was identified within Southwest Research Institute as Project 11-5830-001.

Mr. Robert J. Garbe of the Emission Control Technology Division, Office of Mobile Source Pollution Control, Environmental Protection Agency, Ann Arbor, Michigan, served as EPA Project Officer. Mr. Charles T. Hare, Manager, Advanced Technology, Department of Emissions Research, Southwest Research Institute, served as the Project Manager. The project was under the supervision of Melvin N. Ingalls, Senior Research Engineer, who served as Project Leader and principal investigator. Key personnel in the Department of Emissions Research involved in the project were Kathleen Hanna, Senior Technician, Joyce Winfield, Technician, and Katherine Anderson, Student Scientist.

SUMMARY

The goal of this study was to provide a method of estimating the concentration of any vehicle-generated pollutant in areas where people are in close proximity to vehicles. This close proximity exposure is often referred to as a microscale exposure situation. A list of common microscale exposure situations was extracted from several hypothetical daily activity routines. These situations are:

- Enclosed Space
  - -residential garage
  - -parking garage
  - -roadway tunnel
- Street Canyon
- Expressway
  - -on expressway
  - -beside expressway
- Localized Area
  - -parking lots
  - -industrial sites

For each of the situations, an appropriate dispersion model was selected for use in obtaining pollutant concentrations. However, no model was found for the localized area situations. Two models were combined in a new manner to obtain a single model for the on expressway situation. Section III of the report contains a mathematical description of each of the models selected.

To determine the exposure level in each case, it was decided to calculate the pollutant concentrations in typical and severe actual situations. Real world actual situations were chosen over hypothetical situations to provide more meaningful and defensible pollutant concentration levels. The concept of a "severe" situation was used rather than "worst case," since using the real world worst case requires examining every existing physical situation to find the one worst case.

The range of physical variables for each situation was examined to define the typical and severe cases for each situation. The pertinent variables for each of the situations are summarized below:

- Residential Garages - There are over 34.1 million residential garages in the United States. Multifamily dwellings were not included in this category so that only single family garages are simulated. No data was found on size range. A single car

garage 10 feet wide, 26 feet long, and 8.42 feet high, was chosen for both the typical and severe situations, with pollutant generation time being longer for the severe case. Report Section IV.A, page 22, defines the range of all physical variables of this category.

- Parking Garages - There are over 5,300, possibly as many as 10,000, parking garages in the United States. They vary in parking capacity from under 100 cars to over 4,000 cars. The average capacity is about 400 cars. Most parking garages are above ground with open sides and depend on ambient air circulation for ventilation. About ten percent of the garages have mechanical ventilation. Mechanical ventilation rates vary from four air changes per hour to 16 air changes per hour. The Convention Center parking garage in San Antonio, Texas, was chosen as the typical situation. It is a 5 level garage with a total capacity of 461 vehicles. It is above ground with natural ventilation. The Music Center garage in Los Angeles, California was chosen as the severe case. This garage has 8 levels, 6 of which are underground, with a capacity of 1,582 vehicles. It is entirely mechanically ventilated at a rate of 4 air changes per hour (prior to 1979). Section IV.B, page 23, defines the range of physical variables considered.

- Roadway Tunnels - There are approximately 105 roadway tunnels over 500 feet long in the United States. The longest tunnel is 9,117 feet long. Over half these tunnels are under 2,000 feet in length. Approximately 59 of these tunnels were classed as commuter tunnels. The daily traffic in these commuter tunnels ranged from under 5,000 vehicles per lane per day to over 30,000 vehicles per lane per day. All but three of the commuter tunnels over 500 feet long were mechanically ventilated. Ventilation rates vary from 0.068 $m3$/sec per lane meter to 0.275 m^3/sec per lane meter. The Lowery Hill tunnel in Minneapolis, Minnesota was chosen as the typical tunnel exposure. This 1,496 foot long tunnel has two tubes with three lanes per tube. It has a daily traffic count of approximately 12,000 vehicles per lane. The Baltimore Harbor tunnel in Baltimore, Maryland was chosen as the severe tunnel exposure. This 6,700 foot tunnel has two tubes with two lanes per tube. It has a daily traffic count of 16,375 vehicles per lane. Section IV.C, page 31, covers the range of physical variables considered.

- Street Canyons - There are estimated to be almost 850 miles of street canyons in the United States. In general, the streets are less than seven lanes wide and the buildings under 26 stories. The minimum canyon height to width ratio for a building-lined street to be considered a street canyon is approximately 0.3. Since the street canyon model used was limited to a height to width ratio of 2.0, very narrow, deep canyons were not considered in this study. Houston Street in San Antonio, Texas, between the cross streets of Navarro and St. Mary's was chosen as the typical street canyon exposure. The street is four lanes wide with seven foot wide sidewalks and a height to width ratio of 1.81. Main Street in Houston, Texas, between the cross streets of Capitol and Rusk, was chosen as the severe exposure situation. Main Street is six lanes wide with a 15 foot sidewalk on each side. It has a height to width ratio of 1.39. Section IV.E, page 50 discusses the physical variables of street canyons.

- Expressways - There are approximately 17,000 miles of urban expressways in the United States. Over half of this mileage consists of highways of four or less lanes. Less than one percent of the highway mileage consists of 9 or more lanes. The average daily traffic (ADT) varies from under 10,000 to over 200,000 vehicles per day. The median ADT is between 30,000 and 40,000 vehicles per day. An examination of wind direction relative to expressway orientation revealed that all relative wind directions were equally alike on a nationwide basis. The average wind speed was approximately 7 mph. A section of I-410 on the west side of San Antonio, Texas between U.S. 90 and I-35 was chosen as the typical exposure situation. This four lane urban expressway runs in a NNW to SSE direction and has an ADT of approximately 28,000 vehicles. A portion of the Santa Monica Freeway (I-10) in Los Angeles between Washington and La Brea was chosen as the severe expressway situation. At this section, the freeway is 10 lanes wide with an ADT of over 200,000 vehicles. Section IV.D, page 40 of the report discusses expressway variables and prevailing wind speeds and directions.

Pollutant concentrations were calculated for each typical and severe exposure situation using the chosen dispersion models. Concentrations were calculated using one gram per mile per vehicle for tunnel, street canyon and expressway situations, and one gram per minute per vehicle for the residential and parking garages. The major data and assemptions used for each situation are summarized by category in the following paragraphs:

- Residential Garage - The typical and severe residential garage exposure situations use the same physical setting, but different pollutant generation times. The physical situation chosen was a single car garage with a volume of 2189 cubic feet (10 feet by 26 feet by 8.42 feet). The only ventilation is natural air circulation at a rate of 615 cubic feet per minute. The ventilation factor, as discussed on pages 13 and 66 of the report, was assumed to be 0.25 for the vehicle exhaust equation.

- Parking Garage - The typical exposure situation was chosen as the fourth level of the San Antonio, Texas, Convention Center parking garage following an event at the adjacent Convention Center. This garage is naturally ventilated. With an assumed wind speed of 7 mph, the ventilation rate for the fourth level is 308,000 cfm. The total volume of this level is 356,000 cubic feet. It was assumed that there were 17 active cars on the fourth level at all times during the emptying process. A ventilation factor of 0.4 was used for the vehicle exhaust equation. The severe exposure situation was chosen as the fifth level of the Music Center parking garage in Los Angeles, California. This garage is mechanically ventilated. The ventilation scheme modeled was the pre-1979 ventilation system. The level five volume is 737,316 cubic feet with a ventilation rate of 38,100 cfm. It was assumed that there were 56 active cars on the fifth level at all times during the emptying process. A ventilation factor of C.3 was used for the vehicle exhaust equation.

- Roadway Tunnels - The typical exposure situation was chosen as the morning rush hour in the 1500 foot long Lowery Hill tunnel in Minneapolis, Minnesota. This two tube tunnel has a semi-transverse ventilation scheme with a maximum ventilation rate of 536,000 cfm per tube. The maximum ventilation rate was increased 10 percent to account for the piston effect of the cars. It was assumed that there were 25 vehicles traveling at 45 mph in each tube at all times during the morning rush hour. A ventilation factor of 1.0 was used. The severe tunnel exposure situation used was rush hour in the Baltimore Harbor Tunnel. This 6700 foot long tunnel has a fully transverse ventilation system with a maximum ventilation rate of 800,000 cfm per tube. To this rate is added 50,000 cfm for the piston effect of cars entering the tube. It was assumed that there were 165 vehicles traveling at 25 mph in the tube at all times during rush hour. A ventilation factor of 1.0 was used for this situation.

- Street Canyons - As explained in Section IV, the street canyon conditions that constitute typical and severe exposures depend on the emission type being considered. For some emissions, a severe case is low speed, high traffic density; for others a higher speed, lower density. Street width then becomes the controlling parameter in defining typical and severe situations. A four lane street was used for the typical case, and a six lane street, the severe case.

  The typical case, Houston Street in San Antonio, Texas, is 18.6 meters wide including sidewalks. The street runs in a West to East direction. The average building height is 33.7 meters in the city block used for this situation. The receptor was located on the sidewalk, 8.8 meters from the center of the street, 1.5 meter above street level. Wind direction used was SE to SW at 8 miles per hour. Two traffic conditions were used: 800 vehicles per hour, at 5 mph and 1600 vehicles per hour at 20 mph. The severe case, Main Street in Houston, Texas is 27 meters wide. The average building height in the city block chosen for this situation is 38 meters. The street is orientated NE to SW. The receptor was located on the sidewalk, 11.4 meters from the center of the street, 1.5 meters above street level. The wind conditions used were 0.9 miles per hour, perpendicular to the street. Two traffic conditions were used: 1200 vehicles per hour at 5 mph and 2400 vehicles per hour at 20 mph.

- Expressways - Two types of expressway exposures were considered: the receptor in a vehicle on the expressway and a receptor beside the expressway. The typical on-expressway situation was chosen as a vehicle occupant in the outside southbound lane of IH410 between Valley High Drive and U.S. 90 in San Antonio, Texas during the morning peak traffic period. The complete set of typical situation input values for the despersion model is listed below.

- Highway dimensions
  - -4 lanes, each 3.66 meters (12 feet) wide
  - -median, 13.41 meters (44 feet) wide

- Vehicle volume
  - -900 vehicles per hour per lane on southbound (receptor) side
  - -500 vehicles per hour per lane on northbound side

- Point source (vehicles on receptor side) information
  - -emission strength, 0.0153 g/sec, (1 g/mile at 55 mph)
  - -average of four vehicle lengths between vehicles
  - -average vehicle length, 6.7 miles (22 feet) assumes 80 percent cars, 20 percent trucks
  - -exhaust height assumed to be 0.3 meters (one foot)
  - -10 vehicles in each lane ahead of receptor vehicle

- Line source (vehicles in opposite lanes)
  - -line source strength 0.0862 x 10^{-3} g/sec m lane (1 g/mile per vehicle, 500 vehicles per hour)
  - -bouyancy flux 0.0191 m^3/sec^3

- Receptor
  - -located at center of outside downwind lane
  - -height 1.22 meters (4 feet)

- Meteorology
  - -wind direction, from 357.5 to 270 degrees relative to vehicle direction
  - -wind speed, from 1 m/sec to 6 m/sec (2.2 to 13.4 mph)
  - -stability, Pasquill Class C (slightly unstable)

The severe on-expressway situation was chosen as a vehicle occupant in the middle eastbound lane of the Santa Monica Freeway (IH10) between Washington Boulevard and La Brea

Boulevard on the west side of Los Angeles during the morning peak traffic period. The complete set of severe situation input values for the dispersion model is listed below:

- Highway dimensions
  -10 lanes, each 3.35 meters (11 feet) wide
  -median, 6.71 meters (22 feet) wide

- Vehicle Volume
  -2000 vehicles per hour per lane on eastbound (receptor) side
  -1675 vehicles per hour per lane on westbound side

- Point Source (vehicles on receptor side) information
  -emission strength, 0.01389 (1 g/mile at 50 miles/hr)
  -average of two vehicle lengths between vehicles
  -average vehicle length 6.7 meters (22 feet) assumes 80 percent cars, 20 percent trucks
  -exhaust height, 0.3 meters (one foot)
  -10 vehicles per lane ahead of receptor vehicle

- Line Source (vehicles in opposite lanes)
  -line source strength, 0.2982 x 10^{-3} g/sec m lane (1 g/mile per vehicle, 1675 vehicles/hr per lane)
  -bouyancy flux 0.0638 m^3/sec^3

- Receptor
  -located at center of center lane
  -height 1.22 meters (4 feet)

- Meteorology
  -wind direction, from 357.5 to 270 degrees relative to receptor vehicle direction
  -wind speed, from 1 m/sec to 6 m/sec (2.2 to 13.4 mph)
  -stability, Pasquill Class C (slightly unstable)

I-10 at Silber Road on the west side of Houston was chosen as the severe beside-expressway exposure location. At this location, I-10 runs due east and west, with four lanes in each direction. The receptor location was on the north side of the expressway. The 1977 traffic count was 167,860 vehicles per hour per lane. Wind direction was 90 degrees relative to the road (180 degrees true) and wind speed of 1 m/sec. Neutral atmospheric stability was used. For the long term exposure, Houston wind data indicated that vehicle emissions were dispersed to the north side of the expressway, approximately 60 percent of the time.

A summary of the pollutant concentrations for all the exposure situations considered is given in the following table. Also shown is the section of the report which contains that data and assumptions used in calculating the concentrations. The reader is cautioned to understand the assumptions before using information from this table.

SUMMARY OF MICROSCALE SITUATION CONCENTRATIONS

Situation	Concentration $\mu g/m^3$ [a]		Report Section [b]
1. Residential Garage			V.A page 64
Typical (30 second run time)	7,900		
Severe (5 minute run time)	67,000		
2. Parking Garage			V.B page 71
Typical (parking level)	3,900		
Severe a) inlet air component	9,600		
b) exhaust emission component	46,100		
3. Roadway Tunnel			V.C page 83
Typical	1,123		
Severe	2,856		
4. Street Canyon (sidewalk receptor, includes background)			V.D page 86
Typical a) 800 vehicles per hr	42		
b) 1600 vehicles per hr	85		
Severe c) 1200 vehicles per hr	141		
d) 2400 vehicles per hr	282		
5. On Expressway (Wind: 315 deg. relative, 2.2 mph)			V.E page 96
Typical	124		
Severe	506		
6. Beside Expressway	Short Term	Annual	V.E page 102
Severe ~1 meter	397	61	
10 meters	334	48	
100 meters	105	14	
1000 meters	13.6	1.6	

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[a] For 1 g/vehicle mile (1 g/vehicle minute for garages). Assumes no background concentrations except as noted.

[b] The report section shown contains the data and assumption used to determine pollutant concentrations.

To use these values with emission factors other than one gram per mile or one gram per minute, multiply the concentration in the table by the desired emission factor.

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LIST OF SYMBOLS

C = concentration of pollutant mass/volume

C_o = concentration of pollutant in enclosed space at time $t = 0$. mass/volume

C_1 = Initial concentration contribution to enclosed space concentration

C_2 = ventilation contribution to enclosed space concentration

C_3 = vehicle contribution to enclosed space concentration

C_i = concentration of pollutant in ventilation air

E = efficiency of pollutant filter, if any (0 to 1.0)

F_1 = bouyancy flux, $length^3/time^3$

H = building height, length

h_o = plume center height, length

h_c = effective height of emission source, length

K = turbulent diffusivity of momentum $\sim 1\ m^2/sec^2$

K_c = concentration coefficient, dimensionless

L = block length

m = mixing factor

Q = pollutant generation rate, mass/time

Q_L = pollutant generation rate per meter

R_i = volume rate of ventilation, volume/time

R_f = volume rate of air through filter, volume/time

S = slant distance from source to receptor

t = time

U = wind speed, length/time

V = enclosed space volume $length^3$

W = street canyon width, length

Y = horizontal distance from plume center line to receptor

Z = vertical distance from plume center line to receptor

Greek Letters

δ = penetration depth of rooftop wind into street canyon, meters

σ_y = horizontal dispersion parameter, meters

σ_z = vertical dispersion parameter, meters

I. INTRODUCTION

The exhaust from vehicles powered by combustion engines contains many more compounds than the four exhaust constituents (HC, CO, NO_x, and particulates) currently regulated.(1,2)* In addition, systems designed to control the four regulated emissions can alter the chemical composition of the exhaust.(3,4) Malfunctions of engine and emission control systems can also change the concentrations of the various chemical species in the exhaust.(5,6,7)

The Clean Air Act Amendments of 1977 require vehicle manufacturers to show that each emission control system will not "... cause or contribute to an unreasonable risk to public health, welfare or safety in its operation or function."(8) Thus, in evaluating any proposed emission control system, a manufacturer must determine if any chemical compounds in the exhaust are increased as a result of that system. If such increases occur, the manufacturer must determine whether or not they contribute to an unreasonable risk to public health or welfare.

The EPA, in OMSAPC Advisory Circular 76(9), presented a list of chemical compounds which might occur in engine exhaust pollutants and which the Agency felt might contribute to a public health risk. The list was not intended to be a complete list of possible deleterious compounds. Sampling methodologies and analytical techniques have since been developed for most compounds on the list.(10,11) Thus, it is now possible to determine the exhaust emissions, in mass per distance or mass per time, of many unregulated emissions which have a possibility of "causing or contributing to an unreasonable risk to public health."

Two steps remain in ascertaining if the unregulated emission levels produced by prototype emission control systems meet the requirements of the law. The first is to determine, for a variety of exposure situations, what ambient air concentrations results from the measured exhaust emission levels. The second step is to determine if these ambient air levels pose a public health or welfare problem. This study addresses the first step: the determination of ambient air concentrations for a variety of situations.

A. Objectives

In order to provide ambient air concentrations for enough situations to determine (when combined with health effects) if a given pollutant emission level is a public health problem, this project has four objectives. They are:

1. to identify and classify the situations in which a person is exposed to mobile source pollutants

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*Superscript numbers in parentheses designate references at the end of this report.

2. to choose and make ready for use, mathematical models capable of determining ambient air concentrations from vehicle emission rates for each exposure situation

3. to determine the range of physical variables for each expsoure situation so that "typical" and "severe" exposure cases may be defined

4. to apply the models to determine ambient air concentrations for each exposure situation using the real world "typical" and "severe" situations

B. Approach

Fulfillment of the first objective of this project required a consideration of sites where highway vehicles are used, and the location of people in relationship to the vehicles. This item was accomplished considering the daily routine of individuals in various age groups, occupations, and geographic locations. Similar situations were then grouped together to obtain a minimum number of truly different situations.

The mathematical models for each different situation were chosen from the literature. No attempt was made to develop new models, although existing models sometimes required modification or use in a new way to most accurately define the ambient air concentrations.

The defining of real world typical and severe conditions for each situation was accomplished by searching the literature for physical descriptions of situations, such as the sizes of tunnels and street canyons, determination of time-averaged atmospheric conditions, and on-site investigations of real physical situations. The aim was to define actual places and actual atmospheric conditions occurring in these places that could be classified as typical and severe from consideration of the physical and atmospheric characteristics of each exposure situation. Thus, the need to prove that some arbitrary, hypothetical situation could actually occur was avoided.

Ambient air concentrations for each of the real world exposure situations chosen was obtained by using the parameters from these situations together with the appropriate model. Where the vehicle emission rate is a simple multiplier to the rest of the terms in the model equation, the model was run with a unity emission factor in the correct units for the equation (e.g., one gram/min). Where the vehicle emission factor is rot a simple multiplier, curves of ambient air concentration as a function of emission factor for the given physical situation were produced.

II. SELECTION OF EXPOSURE SITUATIONS

For this project, no definitive investigation of population activity patterns was undertaken, nor is it known if such studies exist in the literature. EPA is currently studying population activity patterns,(12) but the results of that study are not yet available. However, by envisioning possible activity patterns for several different population groups, it should be possible to arrive at most of the common exposure situations.

A. Activity Patterns of Population Groups

Obviously, all people in the United States do not follow the same daily activity pattern. Just as obvious, however, is the fact that large groups of the population do have similar activity patterns. Since the desired result of this investigation is exposure situations involving emissions from mobile sources, the situations investigated should involve areas where there are large concentrations of vehicles. This means that the population groups of interest are in an urban or suburban, rather than rural, setting.

There are many ways of dividing the population by activity groups. Depending on the criteria, a large number of groups could be identified. For purposes of this study, four groups of people were chosen with obviously different activity patterns. These groups are:

- Urban commuter
- Suburban to central city commuter
- Suburban homemaker
- Suburban school child

By following a member of each of these groups through a hypothetical daily activity cycle, those situations involving exposure to mobile source emissions can be identified.

1. The Urban Commuter

The urban commuter is one whose residence is in the urban area of a city. The residence is assumed to be multistoried (four or more stories). The urban commuter commutes by public transportation, with his commuting trip lasting under one-half hour. It is assumed that he both lives and works in an area of multistoried buildings. A hypothetical urban commuter might have a daily activity pattern as follows. In the morning he leaves his residence and walks, in a shallow street canyon, one block to a bus stop; waits 10 minutes at edge of the traffic lane for a bus; rides the bus for 10 minutes through street canyons with morning rush hour traffic; gets off the bus; then walks one block to his work place. His work location is on the first floor of a multistoried, air-conditioned building. At lunch time, he walks one block to a restaurant (air-conditioned) on the first floor of a multistoried building; eats, and returns to his work place. After work, he reverses his morning commuting routine. He spends the evening and night in his residence. From the preceding scenario, it can be seen that an urban commuter's exposure to vehicle emissions is almost entirely in street canyons of various sizes and orientations to the wind. His main exposure is during high traffic hours.

2. The Suburban Commuter

The hypothetical suburban commuter lives in a single family dwelling in a residential area. He commutes to work in a private vehicle. The first encounter with vehicle emissions during his assumed daily activity pattern is when he starts his car in an enclosed garage. His commuting trip to a city central business district (CBD) exposes him to vehicle emissions in the following situations: suburban through streets, expressway, a highway tunnel, and the CBD street canyons. The total trip takes one-half hour and ends in an underground parking garage. He walks one block through a street canyon to his work place. This work place is several floors up in a multistory, air-conditioned building. At lunch time, he walks one block through a street canyon to a restaurant, eats, and walks back. After work he reverses his morning commuting routine. In the evening he attends a professional sports event at a large stadium, using his private vehicle to go to and from the event over roadways that are similar to his commuting route. He returns to his suburban residence following the sports event. From the preceding scenario, it can be seen that the suburban commuter encounters a variety of microscale exposure situations. However, his main exposure is also during high traffic hours.

3. The Suburban Homemaker

The hypothetical suburban homemaker is a woman with two children, whose activity pattern is a great deal more varied than the commuter patterns described above. The homemaker's vehicle emission exposure begins in an enclosed residential garage. The remainder of her exposure during the day results from numerous short, nonexpressway trips in her private car, to such places as schools shopping centers (large and small), etc. Early morning trips, for example to deliver children to school, are made during the peak traffic period. The remainder of the trips are at nonpeak hours. However, she spends more time waiting at signaled intersections than the commuter. Assume that the homemaker also attends a professional sports event in the evening, traveling to and from the event over a variety of roadways in a private car. She spends the remainder of the day in her suburban home. From the above scenarios, it can be seen that the suburban homemaker exposure is primarily from primary and secondary suburban streets and parking lots. The exposure is generally at nonpeak traffic hours.

4. The Suburban Schoolchild

The exposure to mobile source emissions of the hypothetical suburban schoolchild begins while waiting for a school bus beside a suburban secondary street. Assume this exposure lasts 15 minutes, followed by a 10 minute bus ride on suburban streets to the school. Assume the school is a single story, nonair-conditioned building, located within a kilometer of a major expressway. The child has approximately three quarters of an hour outdoor activity during the day. At the end of the school day, the bus trip is reversed. The remainder of the day and all night are spent in the vicinity of the child's suburban home. Thus, the major exposures to mobile source emissions for this hypothetical school child occur while waiting for and riding the school bus, and during outdoor activity near a major expressway.

B. Types of Exposure Situations Derived from Activity Patterns

From the preceeding hypothetical activity patterns, a group of common exposure situations likely to be encountered can be determined. These exposure situations are listed in Table 1 and discussed individually below.

TABLE 1. TYPES OF EXPOSURE SITUATIONS

I. Enclosed space
    A. Residential garage
    B. Parking garage
    C. Roadway tunnel
II. Street Canyons (short term)
III. Expressway
    A. On expressway
    B. Beside expressway
IV. Localized area sources
    A. Parking lots, airports
    B. Industrial and construction sites
V. Mesoscale area (e.g., a suburban housing area)

1. Enclosed Spaces

Several enclosed space exposure situations are identified above. They are listed in Table 1 as the residential garage, parking garage, and roadway tunnel. By their nature, these situations are short term exposures, lasting probably less than 15 minutes except in rare circumstances. However, because of their enclosed nature, these situations have the possibility of producing the highest ambient concentrations of mobile source pollutants. Therefore, this situation was chosen as one of the situations for which a model would be required.

2. Street Canyons

Street canyon exposures, both short term and long term, appeared frequently in the hypothetical activity patterns. Because the buildings along a street canyon inhibit dispersion of the pollutants, street canyons have the possibility of producing high ambient pollutant concentrations. Therefore, street canyons were chosen as one of the situations for which a model would be required.

3. Expressway

Two expressway situations appear in the hypothetical activity patterns. One situation is the commuter exposure on the expressway, the other is exposure in close proximity (within a fraction of a kilometer) to the expressway. The on expressway situation is short term, with a definite possibility of producing relatively high ambient pollutant concentrations. The close proximity situation could be either short term or longer term (on the order of eight hours). Here, too, there is a possibility of relatively high ambient concentrations of mobile source pollutants. Therefore, the expressway situations, both on and beside an expressway were chosen as situations for which models would be required.

4. Localized Area Sources

The hypothetical activity patterns included several mobile source exposure situations in parking lots, such as at a shopping mall or sports stadium. These locations are normally classed as area sources, since the sources of the pollutant are spread over a relatively large area. For purposes of this study, the exposure of interest is within the area source itself. For parking lots, the exposure is obviously of short duration, probably less than one-half hour. Note, however, that for a single parking event the exposure occurs twice, once on entering the parking lot and once on leaving.

Similar area-type sources, while not mentioned in the activity pattern scenarios, can be envisioned. Such sources as airports, trucking terminals and construction sites could all qualify as area sources. Additionally, exposures in these sources could last for a matter of hours, rather than the fraction of an hour assumed for parking lots. For purposes of this report, with its emphasis on short term, high level exposure, this exposure situation will be covered only briefly.

5. Mesoscale Areas

In all of the suburban activity patterns presented above, a large part of each day was spent at a suburban residence. In most cases, the suburban residence will not be in close proximity (within 1 km) to a major mobile pollutant source. At approximately one kilometer downwind, the effect of a single highway is negligible.(13) Therefore, when examining the exposure at a suburban residence, an area large enough to include all the major mobile sources within several kilometers must be included, since the sum of many mobile sources could add up to a value that is not negligible. Areas up to tens of square kilometers in size are often referred to as mesoscale areas. It is this size area that is required for the determination of ambient levels of mobile source emissions at a suburban residence. While the ambient concentrations may not be negligible, they are certainly relatively low when compared to some of the other exposures considered above.

This exposure siutation is of interest when long term, low level exposure is important, such as in the investigation of carcinogens or criteria pollutants which have significant public health hazards. Since this report is concerned with recurring short term exposures, the mesoscale case will not be covered in this report.

III. MODELS FOR DETERMINATION OF AMBIENT CONCENTRATIONS

A. Literature Search

The purpose of this study was to find the best available dispersion models to determine ambient concentrations in the situations chosen, not to develop new models. To obtain the best available models, a literature search was conducted for available dispersion models covering a spectrum of mobile source emissions exposure situations.

To obtain the maximum coverage of the literature, a computerized abstract service, Lockheed Information System's "Dialog," was used. Four data bases were searched: (1) Engineering Index, (2) Enviroline, (3) Pollution Abstracts, and (4) Dissertation Abstracts International. The key words used in the search were "air quality" and "model". The Engineering Index search produced 232 abstracts; Enviroline produced 375; Pollution Abstracts produced 259 abstracts; and Dissertation Abstracts yielded 8 abstracts. In addition, two NTIS published Bibliographies were obtained: (1) "Automobile Air Pollution Atmospheric Motion (1970-1979)" and (2) "Atmospheric Modeling of Air Pollution," Volumes 1, 2 and 3, covering the period 1964 to June 1979. A total 1248 bibliographic listings were obtained (including many duplications).

Of these 1248 listings, approximately 375 were chosen for further screening. Some of these listings were on hand or immediately available from the Southwest Research Institute (SwRI) Library. From references in the literature obtained, additional listings were found. Not all of these were obtained, and of those obtained, not all were used. Nevertheless, the complete list is contained in Appendix C. Literature actually used is, of course, shown in the List of References.

At the beginning of the study it was decided to initially consider only models for nonreactive pollutants. Atmospheric chemical reactions normally require time frames of hours to days. The highest level mobile source exposures are normally of short durations (fraction of an hour). Thus, it was felt that considering atmospheric reactions would add unwarranted complexity to the study at this time. After the methodology has been developed, it may be desirable to include models which consider chemical reactions in the atmosphere for certain long term, low level exposures. Thus, the literature list in Appendix C contains entries relating to reactive models, but these articles have not been reviewed.

The review of the literature concentrated on actual dispersion models, so that a model for each situation could be chosen as soon as possible. The models chosen are defined in the next report section.

B. Model selection

This section covers the analysis performed in selecting a model for each of the exposure situations defined, and presents the algorithm selected.

1. Model Selection Criteria

As the investigation of available models was begun, it became obvious that a set of screening criteria was needed based on the intended use of the models. From the task statement of work and discussion with the EPA Project Officer, a succinct statement of the intended use of the models is:

> "The dispersion models will be used to determine the ambient concentrations of mobile source unregulated emissions to which humans are exposed in various situations."

The first screening criterion considered was: Is the model appropriate for the intended use? It was determined that some general types of models were inappropriate for use with this study.

Air Quality models can be divided into three general categories as listed below:

1. Rollback models
2. Statistical models
3. Physical Simulation models
    a. Box
    b. Gaussian
    c. Mass conservation
        (1). Eulerian (multibox) models
        (2). Lagrangian (moving-cell) models
        (3). Particulate-in-cell and others

Rollback or proportional scaling models do not, strictly speaking, predict ambient concentrations. They are used in the regulatory process to determine if a given control strategy will result in the desired improvement in air quality. Therefore, rollback models are not appropriate for this study.

Statistical models make use of regression analysis to relate pollutant emissions to ambient air quality using data from measured ambient concentrations. The success of a statistical model depends on having a large number of measured concentrations from areas similar to those where the predicted concentrations are desired. Since measured ambient concentrations of unregulated pollutants are not generally available, it is improbable that a statistical model would be applicable to this study.

This leaves what is called here, for lack of a better description, physical simulation models. Physical simulation models all consider the physical situation to be modeled and attempt to apply the basic equations for the movement and dilution of the pollutant emissions in the atmosphere. In theory, these types of models should be applicable to any pollutant and any physical setting. Thus, it is physical simulation models that will be investigated for this study.

The second criterion is that the models initially selected need not consider atmospheric chemical reactions. A third criterion is that the models should have been subjected to validation testing. Where two models are available that have been compared against actual measured concentrations, the one which yields concentrations closer to the measured concentrations the larger percentage of the time will be used. If both models underpredict, this procedure obviously is best. However, if one or both of the models overpredict the choice is not so obvious. There are those who argue that the model which overpredicts should be used to give a "conservative" estimate. However, this approach more often than not just adds to any controversy that may be generated by the use of the model. It would appear more straightforward to use the most accurate model, then apply a clearly defined "factor of safety," if a "conservative estimate" is desired.

It should be pointed out that it may not be possible in all exposure situations to find a model which has been validated. In such cases, the various theoretical aspects of each model must be evaluated. The model chosen should then be the one judged to best fit the physical situation.

2. Enclosed Spaces

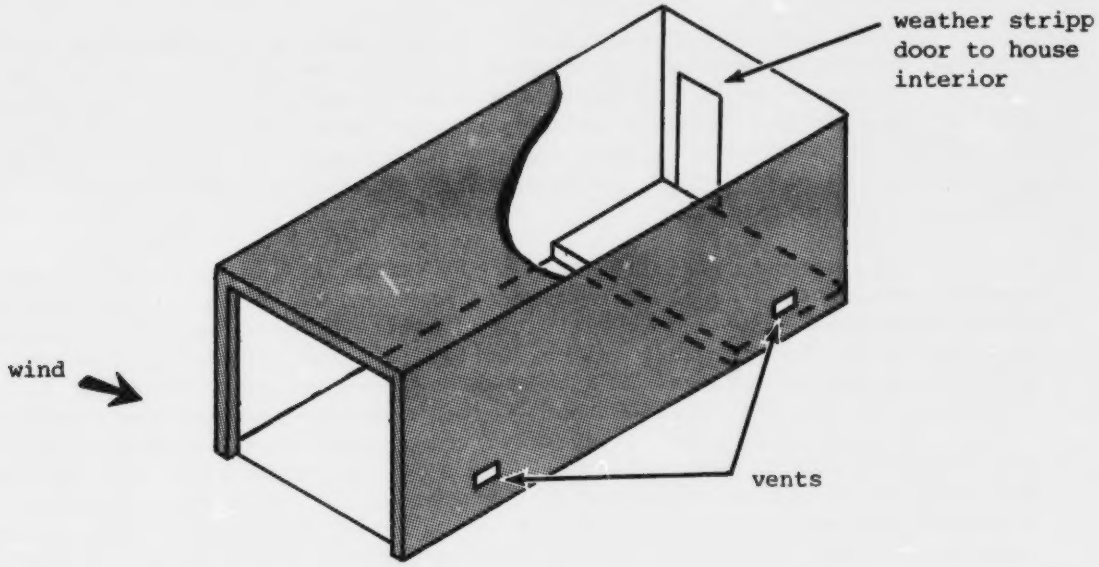
Three exposure situations involving enclosed spaces were identified in Section II. The situations are: (1) private residential garage, (2) roadway tunnel, and (3) parking garage. Sketches of each of these exposure situations are shown in Figures 1, 2 and 3. Ideally, one algorithum should be applicable to all three situations.

Compared to other situations, the literature on enclosed space dispersion models is rather limited, with only 12 abstracts found which might be applicable. Additional articles were obtained from current literature as the project progressed. All references obtained indicate that some form of Turk's Equation should be used for the enclosed space dispersion model.(14,15,16) Other studies derive essentially the same equation independently.(17,18,19,20) The basic form of Turk's Equation that is generally used has been shown to be incorrect in two recent articles.(19,20) The form of the equation used in this study will be that from Reference 20 as shown below:

$$C = (C_o \exp [-(R_i + ER_f)\ F_{v_1} t/V]) + \frac{C_i R_i}{(R_i + ER_f)}\ (1 - \exp [(R_i + ER_f) F_{v_2} t/V])$$

$$+ \frac{Q}{F_{v_3}(R_i + ER_f)}\ (1 - \exp [(R_i + ER_f) F_{v_2} t/V])$$

The equation symbols are defined in the List of Symbols, page xii.


weather stripp
door to house
interior
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vents

Figure 1. Typical residential garage

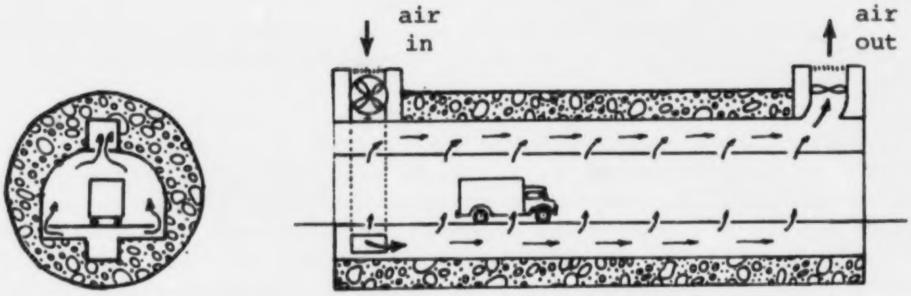
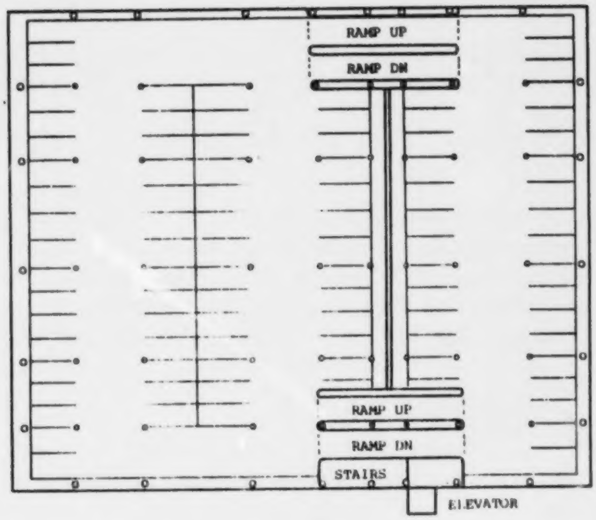
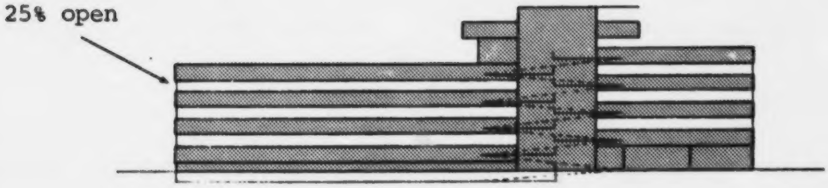

air
in
air
out

Figure 2. Typical roadway tunnel


RAMP UP
RAMP DN
RAMP UP
RAMP DN
STAIRS
ELEVATOR

Floor Plan (one floor)



Elevation

Figure 3. Typical parking garage

While the model has been derived independently by several researchers, little evidence of validation could be found. The studies that did attempt to validate the model used cigarettes as the pollution source and carbon monoxide as the pollutant. The carbon monoxide generation rate of the cigarette, in general, was not accurately known.

For use with this study, it will be assumed that there is no filtering of the pollutant, therefore $E = 0$ and $R_f = 0$. The equation can then be written:

$$C = C_o \exp(-tR_iF_{v1}/V) + C_i\,(1-\exp[-tR_iF_{v2}/V]) + \frac{Q}{F_{v3}R_i}\,(1-\exp[-tR_iF_{v3}/v])$$

Note that this equation assumes constant C_i, Q, and R_i. It is possible to handle step changes in any of these variables by resetting time equal to zero when the variables change. For this study the equation will be broken down into its three component parts to permit easy computation of concentrations for different pollutant rates. The first component is the decay of the ambient concentration:

$$C_1 = C_o \exp(-tR_iF_{v1}/V)$$

The second component is the concentration caused by the pollutant entering with the ventilation air.

$$C_2 = C_i\left[1 - \exp(-tR_iF_{v2}/V)\right]$$

The last component is the concentration caused by the vehicle exhaust.

$$C_3 = \frac{Q}{F_{v3}R_i}\left[1 - \exp(-tR_iF_{v3}/V)\right]$$

but: $Q = nq$

where: n = number of vehicles
q = emissions per vehicle, g/min

therefore:

$$C_3 = \frac{nq}{F_{v3}R_i}\left[1 - \exp(-tR_iF_{v3}/V)\right]$$

The total pollutant concentration in the enclosed space is:

$$C = C_1 + C_2 + C_3$$

For a given situation, each equation can be calculated separately. However, for each instance in which time is reset to zero with a change of C_i, Q or R_i, it must be reset to zero for all equations.

All of the variables in the equations, with the exception of the ventilation factor, can be obtained or estimated from the physical situation to be modeled. The variable termed "effective ventilation factor" (F_v), in this study has been called the "mixing factor" in most studies.

It is important to realize that the model algorithm was derived assuming all pollutants are instantaneously and homogeneously mixed with the enclosed space air. Since this assumption is not true in real situations, a factor was introduced into the equation to account for the real situation behavior. The factor was originally called the mixing factor, and was supposed to be an indication of how well mixed (i.e., homogeneous) the air was. Because of this definition, the factor was assumed to vary bewteen 0 and 1.0 (no mixing to completely homogeneous). The factor, however, did not distinguish between mixing and ventilation effectiveness. In some real situations the pollutant can be removed at a faster rate than if the mixture were homogeneous, requiring a mixing factor greater than 1.0. The term always appears as a multiplier on the ventilation rate in the equation. Thus, it is more properly considered as an effective ventilation factor having a value less than 1.0 when less pollutant mass is removed than would be removed in the pollutant-room air mixture were homogeneous, and greater than 1.0 when more pollutant mass is removed than would be if the mixture were homogeneous. It is interesting to note that although this equation has been in the literature for approximately 20 years, it is only within the past two years that articles have appeared which show the correct placement of this factor in the equation.(19,20) An important part of applying the enclosed space equations will be the defining of the mixing factor for each situation.

3. Alternate Model for Tunnel Exposure Situations

During the course of this project, the Federal Highway Administration published the results of an extensive study of air quality management in highway tunnels.(21,22) This study included a well developed dispersion model called TUNVEN. This model, while starting with the same mass balance as the general enclosed space model, considers the special aerodynamics of tunnels. The TUNVEN computer program was written to obtain numerical solutions for the coupled one-dimensional steady-state aerodynamic and advection equations developed for highway tunnels. While this model was not obtained in time for use in this program, it is recommended for use in any future study of pollutant dispersion in tunnels. Reference 23 contains a listing and user instructions for the TUNVEN program.

4. Street Canyons

Street canyons have been standard areas for evaluating mobile source pollutant contributions for some time, yet the literature on street canyon models is limited. From the twelve articles on hand (24-35) only three algorithms were found.(25,29,31) Of these three, only two(25,31) gave results at any point within the canyon. The third(29) was for "average" street canyon concentrations.

Several investigations(25) of air flow within street canyons have shown that when the rooftop wind is perpendicular to the street, a helical vortex circulation pattern is created in the street canyon, as shown in Figure 4. As would be expected, studies have found that the upwind (referenced to rooftop wind) side of the street has higher concentrations than the downwind side.(25) For the purposes of this study, it is the higher concentrations that are initially of more interest. Therefore, initially only equations for the upwind side of the street canyon will be considered.

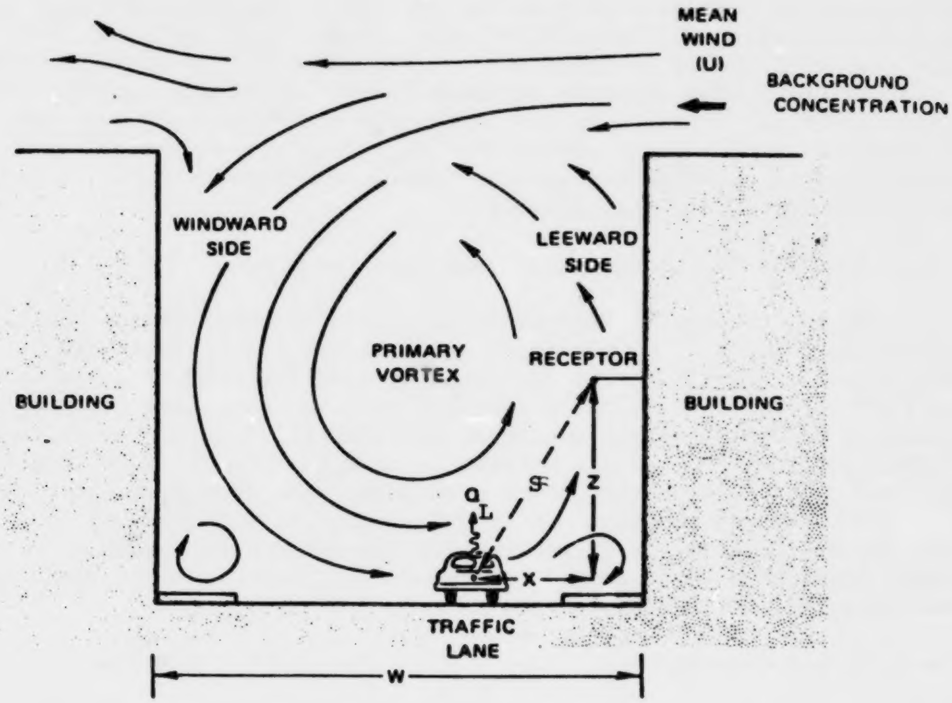

MEAN
WIND
(U)
BACKGROUND
CONCENTRATION
WINDWARD
SIDE
LEEWARD
SIDE
PRIMARY
VORTEX
RECEPTOR
BUILDING
BUILDING
Q
L
S
Z
X
TRAFFIC
LANE
W

Figure 4. Street canyon exposure situation

The algorithm for the upwind side of a street canyon developed by Stanford Research Institute(25,26) was found in two forms:

$$\text{Reference 25:} \quad C = \frac{7\ Q_L}{(U + .5)\ (S + 2)}$$

$$\text{Reference 26:} \quad C = \frac{7\ Q_L}{(U + .5)S}$$

The equation in Reference 26 was said to overpredict the high concentrations and underpredict the low concentrations. The addition of the +2 meters in the equation from Reference 25 may tend to help the correlation somewhat.

A wind tunnel scale model study using an idealized city was performed by Wedding at Colorado State University.(31) He defined a dimensionless concentration coefficient applicable to both sides of the street and all wind directions by the equation:

$$K_c = \frac{C\ U\ H\ L}{Q}$$

It is not clear from Reference 31 whether U is the free stream velocity over the city, roof top velocity, or the velocity in the canyon. There were several illustrations in the reference showing lines of constant K_c over the face of the upstream buildings with the wind perpendicular to the street. The values of K_c at midblock ranged from 19 at 2 meters (full scale height) to 9 at 17 meters (full scale height). The K_c values varied as an inverse exponential function of height. If the vehicle emissions are divided by the block length to obtain emissions per unit length, as in the Stanford model, and H is replaced by the slant height, S, a new concentration coefficient, K_c' can be obtained:

$$K_c' = \frac{K_c\ S}{H} = \frac{C\ U\ S}{Q_L}$$

The new K_c' varies from 7.49 to 8.38 from 2 to 17 meters height at midblock. If 7.75, the value of K_c' at the median slant height, is taken to represent the K_c' values for the whole building face, the values calculated for C would be approximately 3.5 percent high at 2 meters, and 8 percent low at 17 meters up the face of the building. The equation for C would then be:

$$C = \frac{7.75\ Q_L}{U\ S}$$

comparing this to the Stanford equation, Reference 25,

$$C = \frac{7\ Q_L}{(U + .5)\ (S + 2)}$$

it can be said that the wind tunnel testing lends credence to the Stanford model. Obviously for a given U, S, and Q_L the wind tunnel equation will give a higher concentration. Since the Stanford model overpredicts somewhat, using the wind tunnel model would not improve prediction ability. It was therefore decided that the Stanford equation would be used. It should be pointed out that the model should be limited in its use to canyons within certain height to width ratios. The EPA guidelines for evaluating indirect sources(33) indicate that the Stanford equation is only good when the building height exceeds the penetration depth of the rooftop wind. Reference 33 gives the penetration depth as:

$$\delta = 7\left(\frac{KW}{U}\right)^{\frac{1}{2}}$$

For most street canyon and wind conditions that would actually be encountered, the height to width ratios (H/W) would always have to be above 0.3 and often above 0.5. For very narrow or very tall canyons with H/W ratios greater than 2.0, there is evidence that the Stanford model is not applicable, since there is not a vortex circulation at street level.(30,36) In a telephone conversation with John Sontowski of the New York City Department of Environmental Protection, he indicated that he had developed a model for deep street canyons, but that it was not yet available for general circulation.

5. Expressways

There are two exposure situations involving expressways that are of interest. The first is the exposure close (within one km) to the downwind side of an expressway. The second situation is the commuter in traffic on the expressway.

There are a large number of line source dispersion models for calculating concentrations downwind of an expressway.(37-45) Two comparisons (42,46) of predicted to actually measured concentrations indicated that the G.M. model developed by Chock(42) was the most accurate. The form of the Chock model is:

$$C = \frac{Q_L}{U\,\sigma_z\sqrt{2\pi}}\left\{\exp\left[-1/2\left(\frac{Z + h_o}{\sigma_z}\right)^2\right] + \exp\left[-1/2\left(\frac{Z - h_o}{\sigma_z}\right)^2\right]\right\}$$

Here U is the effective crossroad wind (not ambient wind speed) and h_o is the plume center height at distance X from the road. While this model is similar to Gaussian line source models with winds perpendicular to the road, the Chock model is developed in such a way that it can be used in oblique wind conditions without the use of a σ_y. For a complete explanation of the Chock model, see Reference 42. In addition to the usual parameters used in line source computer programs, the Chock model requires a term called bouyancy flux, in m^3/sec^3. The derivation of the bouyancy flux is covered in Reference 42. From the G.M. sulfate experiment, the bouyancy flux, F_1 is taken as:(47)

$$F_1 = \frac{0.052}{1365} \times \left(\frac{\text{number of vehicles}}{\text{hour lane}}\right)$$

The second exposure situation involving expressways is that of the commuter on the expressway. After reviewing the many line source models available, it was determined that all are for emissions off the highway, and are not usable for the on-highway situation. The solution to this situation is best seen as a relative motion problem. Assume the commuting car is stationary, and the rest of the world is rushing by at the vehicle speed. Assume further that the position of the other cars traveling in the same direction does not change relative to the receptor's car. The situation is then as shown in Figure 5. The wind speed is the relative wind, combining the ambient wind and vehicle speed. The vehicles ahead of the receptor are then considered stationary point sources. Some work has been done to show that, even though there is a turbulent wake behind each vehicle, the pollutant dispersion is still Gaussian.(48) Thus, the standard point source Gaussian plume dispersion model can be used. The form of the equation to be used is:

$$C = \frac{Q}{2\pi\sigma_y\sigma_z U} \exp\,[-\,0.5\;y^2/\sigma_y{}^z]$$
$$\{\exp\;[-\,0.5\;(Z-h_c)^2/\sigma_z{}^2] + \exp\,[-0.5\;(Z-h_c)^2/\sigma_z{}^2]\}$$

The standard deviations, σ_y and σ_z, normally used in the Gaussian dispersion equation are for tall stacks in open country. Thus, for cars on a highway, new standard deviations should be determined. These could probably be determined from References 31, 48, 49 and 50.

From Figure 5 it can be seen that the traffic lanes in the opposite direction are line sources to the receptor. Thus, the contribution from these line sources must be added to the point source contributions of the cars ahead of the receptor. The model chosen for evaluation of expressway concentrations should be one that is capable of handling both multiple point and line sources. The EPA model "PAL" is just such a model.(51) However, in its standard form PAL uses the HIWAY line source model, not the Chock model desired. It also does not have the capability to calculate the required relative wind direction and speed. Therefore, a new computer program for the on-expressway model was developed. The program, called ONEX, uses the basic input and structure of the EPA PAL computer program. The following are the major changes:

a. The horizontal line source subroutine was removed and replaced with the Chock line source model.

b. Relative wind speed and direction are calculated based on ambient wind and vehicle speed and direction.

c. Relative wind is used in the calculation of point source concentrations.

d. PAL subroutines for area sources and curved line sources are not included.

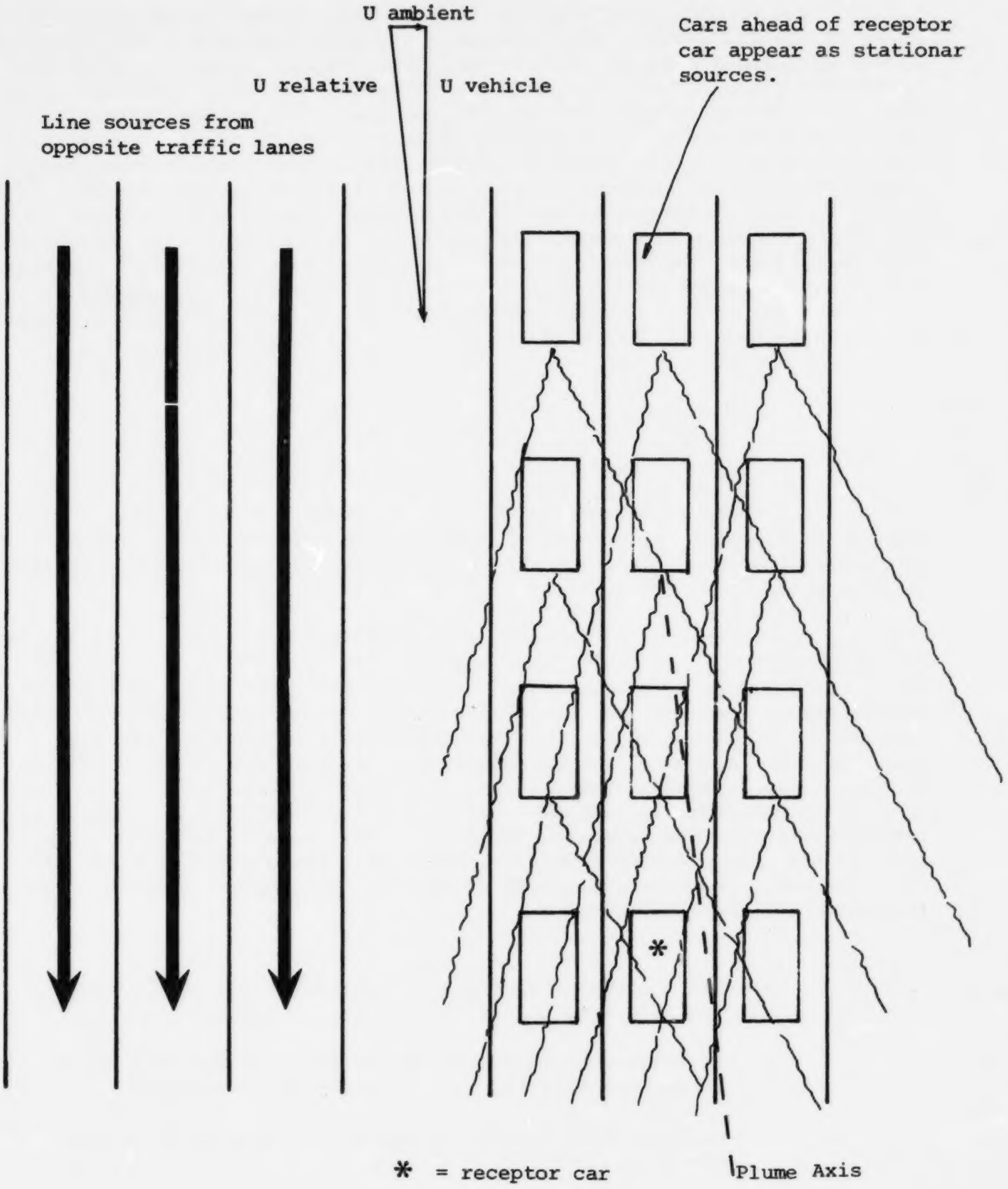

U ambient
U relative
U vehicle
Cars ahead of receptor car appear as stationar sources.
Line sources from opposite traffic lanes
* = receptor car
Plume Axis

Figure 5. Expressway exposure from a relative motion aspect

One of the major concerns with the method of determining the on-expressway concentrations was that the point source dispersion coefficients used in PAL (and most other point source Gaussian models) would not be correct for a line of cars on an expressway. Data from three dispersion studies were used in an effort to determine dispersion coefficients for vehicles in traffic.(31,49,50) Preliminary evaluation of the data indicated that the dispersion coefficients obtained from these studies fall between the standard dispersion coefficients for "neutral" and "unstable" atmospheric stability classes. Therefore, the standard dispersion coefficients were retained for the present. Appendix A contains a study to validate the ONEX model using sulfate levels taken inside vehicles during the G.M. sulfate experiment.

6. Localized Area

Localized area exposure can occur in a variety of situations such as shopping mall parking lots or sports stadium parking lots, trucking terminals, and construction sites. A search was conducted for models that predicted concentrations within these areas. Several models were found that predicted concentrations downwind of area sources, but none were found that predicted concentrations within the area source itself. Since it was not the purpose of this project to develop models for the situations studied, no attempt was made to derive a model for the localized area exposure situation.

C. Model Use

Using the models chosen in the preceding section, ambient concentrations of vehicle emissions can be calculated for a variety of everyday exposure situations if the emission rate from the vehicles and the physical situation are defined. The ultimate end use of these ambient air concentrations will be as a step in determining if any unregulated mobile source pollutant poses a risk to public health or welfare. The other steps in the process are: (1) from knowledge of population activity patterns determine the amount of time spent in each exposure situation (per hour, day, week, year or whatever timeframe desired); (2) from average respiratory rates, exposure time and ambient concentration, determine the total mass of pollutant inhaled for each exposure situation; (3) sum the inhaled mass from each exposure situation to obtain the total dose of pollutant during the timeframe chosen; (4) make a judgement as to whether or not the total dose is a risk to health or welfare.

For an accurate assessment of the health risks, the physical exposure situations that determine the ambient air concentrations, must be as representative as possible. Defining representative situations, whether "typical" or "worst case," requires gathering a large amount of information concerning actual physical settings for each situation. In fact, to define the actual worst case (as opposed to some hypothetical worst case) all physical situations would have to be investigated. Even if the worst case were found, it is possible that it would affect so few people that it would be of no use in defining a health hazard to the general population.

Rather than use a "worst case," the concept of a "severe case" is used in this study. Consideration of meteorology, traffic and physical location can lead to choices of actual physical situations which tend to maximize ambient concentrations, and which affect large numbers of people. While the chosen actual physical location may not be the absolute worst case, it will certainly produce ambient concentrations approaching a worst case.

Many different vehicle emission species are to be investigated using this methodology. It would therefore be convenient if the modeling results for each of the exposure situations were expressed in a form which would allow determination of the ambient concentrations for each different emission specie by a simple calculation involving only the emission rate for that specie. Fortunately, the models chosen in the previous section have the emission rate as a multiplier to the rest of the equation terms. Therefore, each exposure situation can be modeled using a unity value for the emission rate (one gram per mile or one gram per minute, as appropriate). The resulting ambient concentration need only be multiplied by the correct emission rate to obtain the correct ambient concentration for the desired exhaust pollutant.

IV. RANGE OF PHYSICAL VARIABLES FOR EXPOSURE SITUATIONS

The key to the success of this study is to adequately define the range of physical parameters of real exposure situations. With the range defined, typical and severe situations can be properly chosen. As work on the project progressed, it became evident that definition of the range of physical parameters for the various situations was not a trivial task. In no case was the information readily and completely available in the literature. For each exposure case, several agencies or or organizations had to be consulted. Often the information obtained was incomplete. In some cases the information required was not available at all. Where necessary, judgement was used to reconcile apparently conflicting statistics. The descriptions presented here are the most complete that could be assembled after a diligent search and evaluation of the information sources.

A. Residential Garage

The residential garage is a common situation for exposure to automotive pollutants. There were approximately 56.8 million single-family homes in the U.S. in 1980.(52,53) Approximately 60 percent of these homes had garages,(53,54) for a total of 34.1 million residential garages in the U.S. in 1980. Note that this figure does not include garages for multi-family dwellings such as apartments or condominiums. Statistics on the number of garages with multi-family dwellings could not be found. Therefore, the total number of garages given above should be considered a minimum estimate.

The number of persons encountering a residential garage exposure each day is difficult to estimate. Not all garages are used to house cars, having been converted after construction to additional living space. In multi-car families, the most used car may not be housed in the garage. However, if it is assumed that 50 percent of the garages house a car that is used daily, the number of persons exposed to this situation each day is at least 17 million.

No nationwide description of residential garage characteristics was found. Therefore characteristics of residential garages built in the San Antonio area will be assumed to be typical of garage construction nationwide.

According to local building codes, a single car garage must be at least 10 ft wide, 20 ft deep and have at least 8.42 ft ceiling height. Typically, an additional 6 ft in depth is provided for storage space and for appliances, such as washer, drier, and water heater. Nominal auto-access doorways or garage door must be at least 8 ft wide by 7 ft high. The type of door used varies with individual contractors or architectural preference. Since the garage is specifically for auto storage at least 288 square inches of "free air vent" must be provided for either a single or double car garage. Most garages are joined to the house structure with at least one wall common to the interior of the house, through which access to the garage from the interior is made.

Locally, most residential garages incorporate an "overhead door" for the garage door. This door is made of hinged sections on guide tracks which allow it to be lifted vertically and "rolled" up and back, parallel with the ceiling. Some garages are not finished except for walls which are common to interior living space. These common walls are generally insulated and somewhat fire resistant, as prescribed by building codes. If other walls are finished, insulation is not generally used. Some garages also have an open ceiling in which the structural members of the roof are exposed, while others have finished ceilings. Among appliances mentioned, the water heater is generally located in the garage space. The gas water heater is enclosed in a "sealed closet" with three vents, one to supply air for combustion, one to prevent buildup of natural gas in case of malfunction and one which serves as a flue for combustion products. (55)

The residential garage exposure is, in general, extremely short term. A typical exposure scenario might be as follows: receptor enters garage, opens garage door, starts car and allows 30 seconds to warm-up at fast idle, backs car out of garage, returns, closes garage door and leaves. A severe exposure might be as follows: on a cold winter morning, receptor enters garage, opens garage door, starts car and returns to inside of home while car warms up at idle. After approximately five minutes receptor returns to garage, backs out car, closes garage door and leaves. The garage used for both these situations will be a single car garage.

B. Parking Garages

Another source of exposure to automotive pollutants is the parking garage. Parking garages are growing in popularity in crowded downtown areas, high rise office and apartment buildings, and shopping malls. Despite this growing popularity, statistics on parking garages are difficult to locate.

Two primary sources of older information are available. The first is the Highway Research Board Special Report 125 "Parking Principles," dated 1971.(56) This report analyzes several studies done between 1960 and 1968. The information presented in Table 2, showing the average number of garage spaces and garage spaces as a percent of total spaces, is from this publication. To obtain the average number of garages, it was assumed that for all "urban places" over 250,000 people, the average garage size is 500 spaces and below 250,000 people, the average garage size is 300 spaces. The total number of garages in the United States using the 1970 census listing of "urban places," circa 1965 was approximately 1300, as shown in Table 3.

The second source is a parking study conducted by the National League of Cities in the early seventies, and published in 1972 under the title "National Parking Facility Study.(57) This study relied on a mail questionnaire for information. Thus, not all needed information was collected. For instance, the data on number of parking garages was collected by city. However, there was no data for New York, Chicago, Los Angeles, or Philadelphia - the four most populous cities in the country according to the 1970 census.(53) The study reported that there were an estimated 2040 public (either municipally or privately owned) parking garages in the country.

TABLE 2. AVERAGE NUMBER OF PARKING GARAGES BY URBANIZED AREA SIZE

Population Group of Urban Area	No. of Cities Studied	Average Pop. of Sample	Garage Space as % of Total	Avg. No. of Garage Spaces	Average No. of Garages
10,000-25,000	6	17,000	0	10	0
25,000-50,000	6	37,000	3	140	0.4
50,000-100,000	30	68,000	5	260	0.8
100,000-250,000	33	160,000	11	820	2.8
250,000-500,000	16	360,000	16	1,940	4.0
500,000-1,000,000	15	720,000	30	6,900	13.6
Over 1,000,000	5	3,700,000	31	18,600	36.5

TABLE 3. TOTAL PARKING GARAGES BY URBAN AREA SIZE
CIRCA 1965

Population Group of Urban Places	No. of Urban Places in Group[a]	Average No. of Garages	Total Garages
25,000-50,000	520	0.4	208
50,000-100,000	240	0.8	192
100,000-250,000	100	2.8	280
250,000-500,000	30	4.0	120
500,000-1,000,000	20	13.6	272
Over 1,000,000	6	36.5	219
		Total U.S.	1291

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[a] per 1970 Census

The raw data from the study(57), which was included in an appendix of the study, was reanalyzed for this project using Standard Metropolitan Statistical Areas (SMSA's) rather than cities. Included in these data were the number of parking garages in New York, Los Angeles, Chicago, Philadelphia and Houston, taken from counts of listings in the Yellow Pages of the various telephone directories. The results of this analysis are shown in Table 4. The total of 2653 garages, should be taken as representing the public parking garage population in 1972. This value would represent an increase of 194 garages per year between 1965 and 1972.

To bring the garage population estimate up to 1980, it is necessary to examine the construction levels since 1972. From a search of "Parking" magazine issues between 1972 and 1970, construction totals reported by the National Parking Association were obtained for 1972, 1974, 1978 and 1979.(58,60) These construction totals are shown in Table 5.

If the annual construction for the years when data are missing is estimated to be equal to the lowest annual total found (i.e. 302 in 1978), then the total number of parking garages built between 1972 and 1979 was 2647.

In a discussion with engineers at Allright Auto Parks, Inc., one of the largest operators and parking garage consultants in the country, it was learned that relatively few parking garages are taken out of service each year. Expressed as a percentage of new garage construction, the number would be much less than ten percent. Therefore, for all practical purposes the number of garages constructed each year can be taken as the garage population increase for the year. Adding the number of garages built since 1972 to the number of parking garages at the start of 1972, (2653, as presented in the last progress report) the estimated 1980 garage population of 5300 is obtained.

An effort was made to obtain parking garage construction figures from the F.W. Dodge Division of McGraw-Hill. "Parking garage" is one of the categories for which they compile construction reports. However, the cost to obtain reports of parking garage construction over the past eight years was considered too large an expenditure for the information obtained, and the matter was not pursued further. However, the Dodge estimate of nationwide parking garage construction in 1979 was obtained. Dodge lists 720 total parking garage projects in 1979 with a total floor area of 55 x 10^6 square feet. Note that this is more than twice the projects reported by the National Parking Association (NPA) in "Parking" magazine.

This discrepancy in the number of parking garages is reconcilable when the sources of information are considered. The NPA is an association of parking garage designers and operators. The NPA construction estimates are dependent on reports from their members. These companies would likely be involved in the larger projects intended for use by a large segment of the general public. Small projects associated with banks, office building,

TABLE 4. TOTAL PARKING GARAGES FOR STANDARD METROPOLITAN STATISTICAL AREAS-CIRCA 1972

SMSA Size Group	No. of SMSA in Group(a)	Average No. of Garages	Total Garages
50,000-100,000	27	---	0
100,000-250,000	111	4.0	444
250,000-500,000	60	10.6	636
500,000-1,000,000	33	8.1	267
1,000,000-2,500,000	25	32.8	820
Over 2,500,000	8	60.8	486
Total	264		2653

TABLE 5. PARKING GARAGE CONSTRUCTION BETWEEN 1972 AND 1979

Year	Number of Projects Reported[a]
1972	451
1973	(302)[b]
1974	363
1975	(302)
1976	(302)
1977	(302)
1978	302
1979	323
Total	2647

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[a] Reported the National Parking Association as listed in Parking magazine.

[b] Numbers in parentheses are estimates using the lowest number from the 1972, '74, '78, and '79 reported projects.

apartments or universities would not always be reported. F. W. Dodge on the other hand, through its network of field reporters, endeavors to report on all construction. Dodge is therefore more likely to include smaller projects not reported to the NPA. This likelihood is supported by examining the total floor area of the 720 projects reported by Dodge. If the floor area per car for a self-park garage is taken as 300 sq. ft.(61), the 55 X 10^6 sq. ft. total floor area yields an average of 244 spaces per garage. This is approximately half the size of the average garage reported by the NPA. Apparently, the Dodge estimate includes a large number of smaller private parking garages, not reported by the NPA. Assuming this discrepancy has always existed, it is entirely possible that the number of parking garages in the country is actually twice the 5300 estimated from the NPA data. The conclusion to the analysis of this potpouri of information is that there are currently at least 5300 parking garages in the country and quite possibly as many as 10,000 parking garages.

Most literature on parking garages quotes, without supporting data, 400 to 500 spaces as the average size of a parking garage.(56,61) As can be seen from the 1979 Dodge data quoted above there is some evidence that when all types of parking garages are considered the average size may be between 200 and 300 spaces. The only complete size distribution data that could be found was the July 1973 issue of "Parking" magazine.(58) Of the 451 parking garage projects reported to the NPA in 1972, 381 included number of spaces. The size distribution of these garages is shown in Figure 6. A partial distribution for 1979 construction was contained in April 1980 issue of "Parking".(60) This partial distribution is also shown in Figure 6. Note that the 1979 distribution is similar to the 1972 distribution. The median garage size for this distribution is approximately 600 spaces. If the garages were assumed clustered at the midpoint of each interval, the mean would be approximately 740 spaces. Thus, depending on which figures are being used, and how "average" is defined, an average parking garage could contain anywhere from about 250 to 740 spaces. Given this variation, using 400 to 500 spaces as an average parking garage size does not seem unreasonable.

If the figures derived from NPA data are used for number of garages (5300) and average size is taken as 500 spaces, then the number of national daily parking garage exposures would be a minimum of 3.7 million people; assuming the number of cars using a garage during a day is equal to the number of spaces, and that there are 1.4 persons per car.

References 56 and 61 state that most garages are above ground, and that most of these are of open side design. Thus, ventilation for the majority of garages is natural, and affected by local microscale climatic conditions. Reference 62, which modeled diesel particulate in parking garages, states that 0.5 mph wind through an open side garage is approximately equal to one CFM per square foot of floor area.

Mechanical ventilation is required in enclosed parking garages which are mainly underground garages. Only 46 of 451 (10.2 percent) garage construction projects reported by the NPA in 1972 were wholly underground,(58) requiring mechanical ventilation. If this fraction were extrapolated to the entire garage population, there would be between 500 and 1000 mechanically

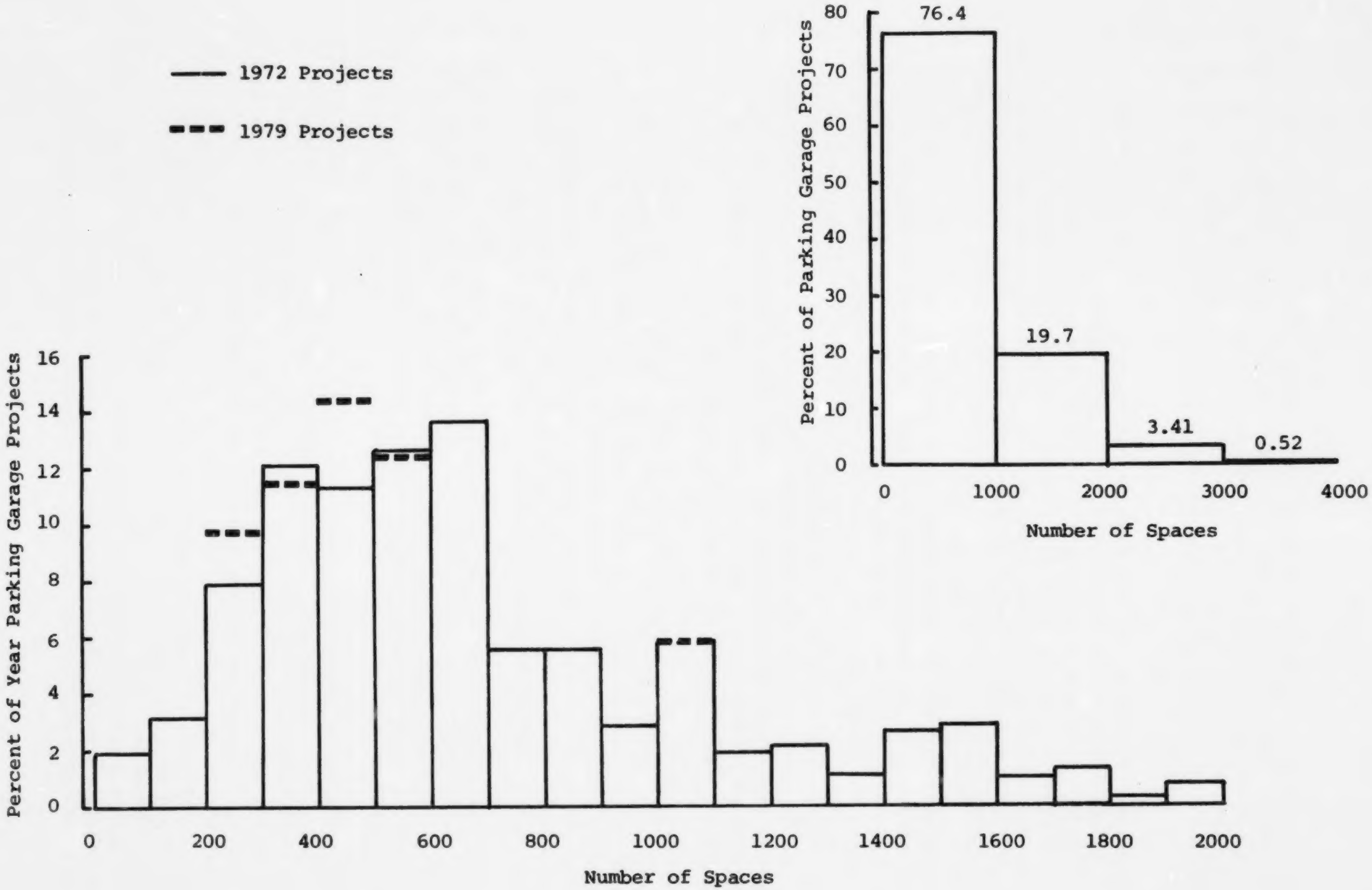

Figure 6. Size distribution of parking garage projects - 1972 and 1979

ventilated garages. The amount of ventilation used depends mainly on local building codes. Most building codes require four to six air changes per hour. The New York City Building Code required a minimum ventilation rate of one CFM per square foot of garage floor area. Using the recommended floor-to-ceiling height(56) of seven feet, this rate produces approximately eight air changes per hour.

Actual ventilation rates are difficult to obtain. A 1961 article in the American Industrial Hygiene Journal(63) and a 1973 article in "Parking" magazine(64) did list some ventilation rates for underground garages. These rates are listed in Table 6. The Los Angeles Music Center Garage ventilation rates were obtained from Hayakawa Associates of Los Angeles, who were contracted to revamp the Music Center garage ventilation. This work was completed in 1980.

Operational factors can also have effect on emission concentrations in a parking garage. In an article which discussed CO emergency situations in parking garages(64), the main cause of these situations was identified as a backup at the exit lane (or lanes). These backups occurred when, for one reason or another, all cars tried to exit at the same time (end of a parade, work day, etc.). If there were insufficient exit lanes, and if the streets onto which the cars exited could not handle the traffic, a backup occurred. In addition, situations which require parking payment upon exiting slowed down the exit process considerably. To avoid this, many garages charge a flat rate per event, collected upon entrance to the garage.

The information discussed above can be used to define the typical and severe exposure cases. The typical garage is an above ground garage, with open sides for natural ventilation and a capacity of 400 to 500 cars. The Convention Center parking garage in San Antonio, Texas meets these criteria and was chosen as the typical parking garage exposure case. A complete description of the garage is included in Section V, where the ambient concentration in the garage is estimated using the enclosed space model.

The severe exposure case would be a garage with a capacity of 1500 or more cars, mechanically ventilated, with a ventilation rate of under 300 cfm/space (or 4 air changes per hour), and often used for single events. The parking space-to-outbound lane ratio should be greater than 250 spaces per lane, and it should exit onto a crowded street.

During the investigation of possible severe case parking garage exposures, it was discovered that the Music Center Garage in Los Angeles was undergoing extensive modification because of poor ventilation. A comprehensive study was done on the garage in its original configuration to determine the necessary improvements. The original garage ventilation, at four air changes per hour, was within, but at the low end of, the building codes at the time of its construction. As can be seen from Table 6, the garage has a capacity of 1582 spaces and is often used for event type parking. Since considerable study has already been done on the garage, there was the possibility of obtaining much more comprehenisve data than would usually be available. After Mr. Robert Magusin, Project Manager in the County Engineer's Office and Mr. H. Endo of Hayakawa Associates, the County's Engineering Consultant

TABLE 6. VENTILATION RATES FOR SOME MECHANICALLY VENTILATED PARKING GARAGES

Name of Garage and Location	No. of Levels	Total Capacity No. of Spaces[a]	Total Ventilation CFM	CFM/Space	Air Changes Per/Hr.	CFM/FT^2
Grant Park Chicago, Illinois	2	2,359	1,766,400	750	16.8	2.2
Pershing Square Los Angeles, Calif.	3	2,000	488,000	244	6.3	0.9
Union Square San Francisco, Calif.	4	1,700	390,000	230	6.0	0.9
Grand Circus Park Detroit, Mich.	2-3	1,100	540,000	490	11.3	1.5
Military Park Newark, New Jersey	3	1,031	400,000	388	10.0	1.15
Mellon Square Pittsburgh, PA.	6	897	245,340	273	7.8	1.0
Brooklyn Civic Ctr. New York City, N. Y.	3	700	240,000	343	8.3	1.14
Lincoln Center New York City, N. Y.	2	610	277,000	454	8.1	1.11
Music Center Los Angeles, California	8	1582	340,000	215	4.0	0.6

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[a] Floor area per space ranges from 270 to 410 sw. ft./space

Source: (1) Journal of the American Industrial Hygiene Ass'n., Dec. 1961
(2) Parking magazine, Oct. 1973

for the work, were contacted to ensure that the data was available, the Los Angeles Music Center Parking Garage was chosen as the severe exposure case. A complete description of the garage is included in Section V, where the ambient concentrations in the garage are estimated using the enclosed space model.

C. Roadway Tunnels

Roadway tunnels are another enclosed space where people are exposed to automotive pollutants. It was decided to limit the investigation to tunnels over 500 feet (152 m) in length; since even at a dead crawl of five miles per hour, it would take only 68 seconds to traverse a 500 foot tunnel. While length is an indication of exposure time, vehicle speed through the tunnel also determines exposure time. The pollutant concentration obviously increases as ventilation rate decreases and number of cars in the tunnel at any given time increases. Thus tunnel length, vehicle speed, traffic density and tunnel ventilation rate must also be considered when chosing typical and severe exposure situations.

Several sources were used to compile a list of tunnels over 500 feet long. "Highway Tunnel Operations" by the Transportation Research Board(65) contains a list of mechanically ventilated tunnels over 500 feet long. A list of toll tunnels(66) was obtained from Mr. Tom Benedict of the FHWA in Washintgon, and an "unofficial" list of road tunnels was obtained from Mr. Jim Washington of the FHWA Bridge Division, also in Washington. Additionally, a list of road tunnels in Colorado was obtained from Mr. Burrell Gerhardt of SwRI, who was previously with the Planning and Research Division, Colorado Division of Highways. Mr. Bill Rush of the International, Bridge Tunnel and Turnpike Association in Washington, D.C. was also contacted regarding toll tunnels.

From this information, a list of 105 road tunnels was compiled. Parallel tubes serving the same road were counted as one tunnel even if they were of different lengths or were built at different times or had different names. The list, included in this report as Appendix B, should not be taken as a complete, official list. It probably contains at least ninety percent of the tunnels in the country. Thus, a good estimate of the number of road tunnels over 500 feet long in the U.S. would be under 120.

The number of tunnels in the U.S. will probably not increase greatly over the next 20 years. Tunnels are more expensive to build and more expensive to maintain than other highway elements.(65) Thus, they tend to be used only at locations where thorough study indicates such costs can be justified. Currently, several (four to six), tunnels are in the planning stage for I-70 east of Glenwood Springs in Colorado.(67,68) In addition, Reference 66 lists seven possible toll tunnels under consideration. Of these only two are new locations; the remaining five are parallel tubes for existing tunnels.

Figure 7 shows the distribution of tunnels by state. Note that the majority of the tunnels are concentrated in a few states. The tunnels were divided into two classes, intercity and commuter, depending on their probable use. Intercity tunnels were those carrying primarily highway traffic (noncommuter) between cities. Commuter tunnels were those used for daily commuting to and from areas of high population density. Of the 105 tunnels, 59 were classed as commuter tunnels and 46 as intercity tunnels. The tunnels were classified by length categories for both tunnel types. Figure 8 is a bar graph of the number of tunnels in each length category for both commuter and intercity tunnels. Note that for both tunnel types, over half of the tunnels are less than 2000 feet long.

The average daily traffic (ADT) was available for 47 of the tunnels (29 commuter, 18 intercity). The tunnels were classified in terms of ADT/lane for both commuter and intercity tunnels. Figure 9 is a bar graph of the number of tunnels in each ADT/lane interval. For all the intercity tunnels, the ADT/lane was 10,000 or less. By contrast, over half of the commuter tunnels had an ADT/lane of over 10,000. From this examination, it can be seen that not only are commuter type tunnels more numerous, they also represent the majority of the exposure "events" (considering one vehicle going through a tunnel one time as an exposure "event"). Thus, only commuter type tunnels will be considered in chosing typical and severe tunnel situations.

An estimate of the number of persons encountering a tunnel exposure situation per day can be obtained from the number of tunnels and the ADT. Assume that the list of 59 commuter tunnels compiled for this project contains all the commuter type tunnels in the country, that the average commuter tunnel ADT is approximately 52,000, and finally that the average car carries 1.4 persons.(69) The total number of tunnel exposures is then approximately 4.3 million per day. If it is assumed that persons going one way through the tunnel in the morning return through the tunnel in the opposite direction in the evening, then 2.15 million people encounter tunnel exposure twice a day.

An excellent summary of the relationship between traffic speed, density and rate (vehicle/hr) for tunnels is contained in Reference 21. Figure 10, which is Figure 10.2 in Reference 21, shows the relationships based on Lincoln Tunnel data.(22) The Lincoln Tunnel data plus data taken during the study reported in Reference 21 indicate a practical peak flow limit of about 1500 to 1600 vehicles/hr per lane, with a corresponding traffic density of 125 vehicles per mile per lane.

Depending on the traffic control of the particular tunnel, during rush hour the traffic density may or may not increase above peak flow toward congested flow. Obviously, from an exposure standpoint, congested flow causes the most severe exposure, both because it increases the traffic density and because it decreases the vehicle speed. It should be pointed out that it is necessary to know both traffic rate and speed to determine if a tunnel is in the congested mode. The tunnel with the highest ADT/lane will not necessarily provide the most severe case from a traffic congestion standpoint.

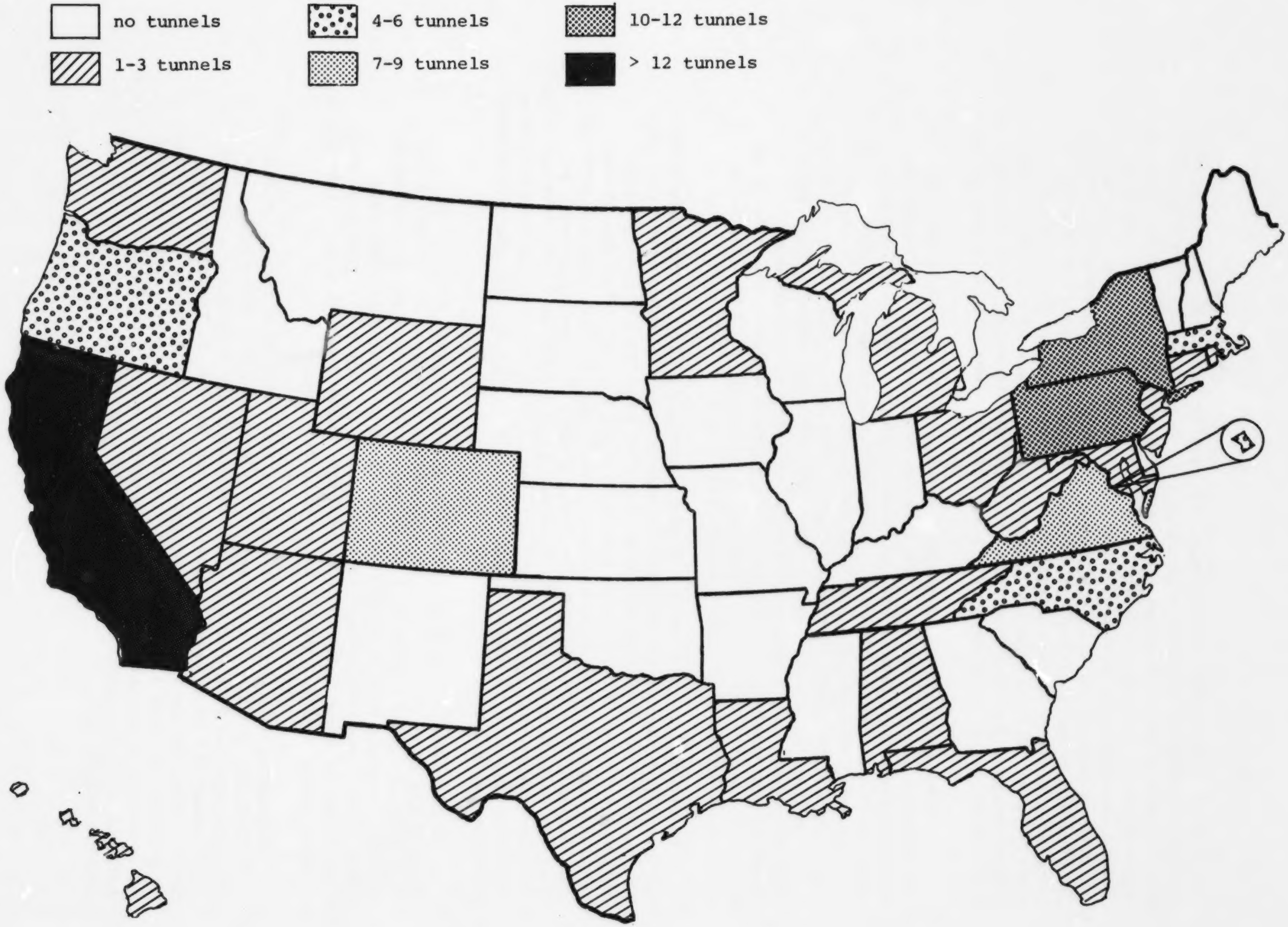

no tunnels
1-3 tunnels
4-6 tunnels
7-9 tunnels
10-12 tunnels
> 12 tunnels

Figure 7. Road tunnel distribution in the United States

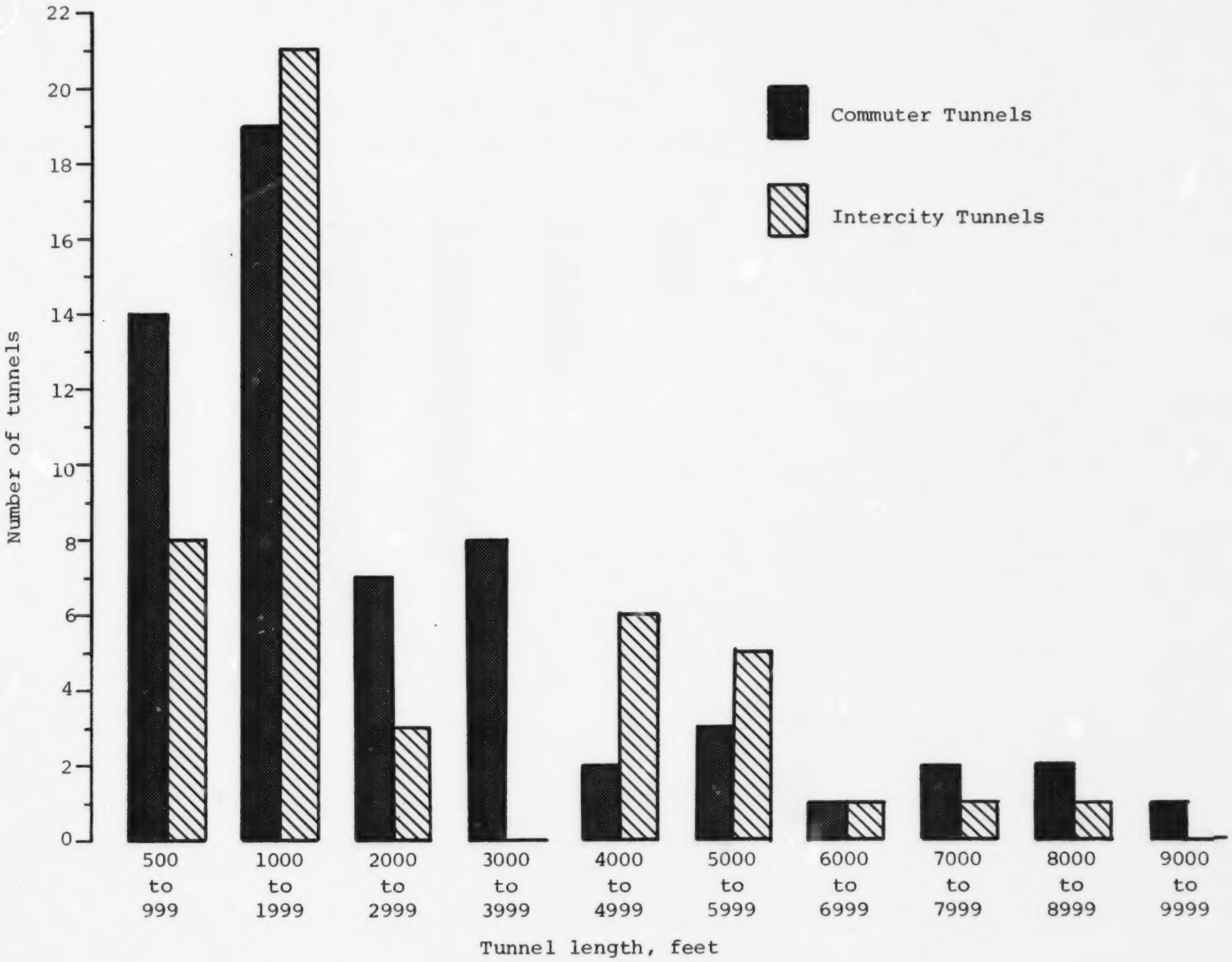


Figure 8. Tunnel length distribution

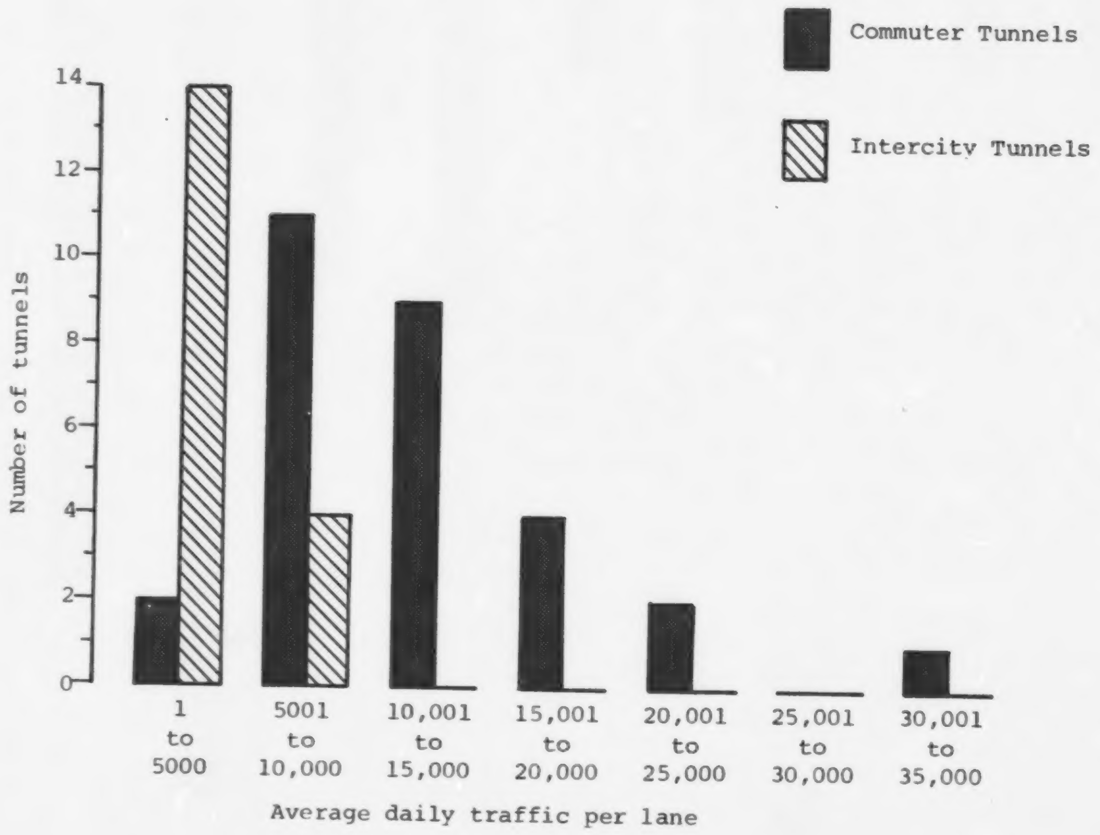
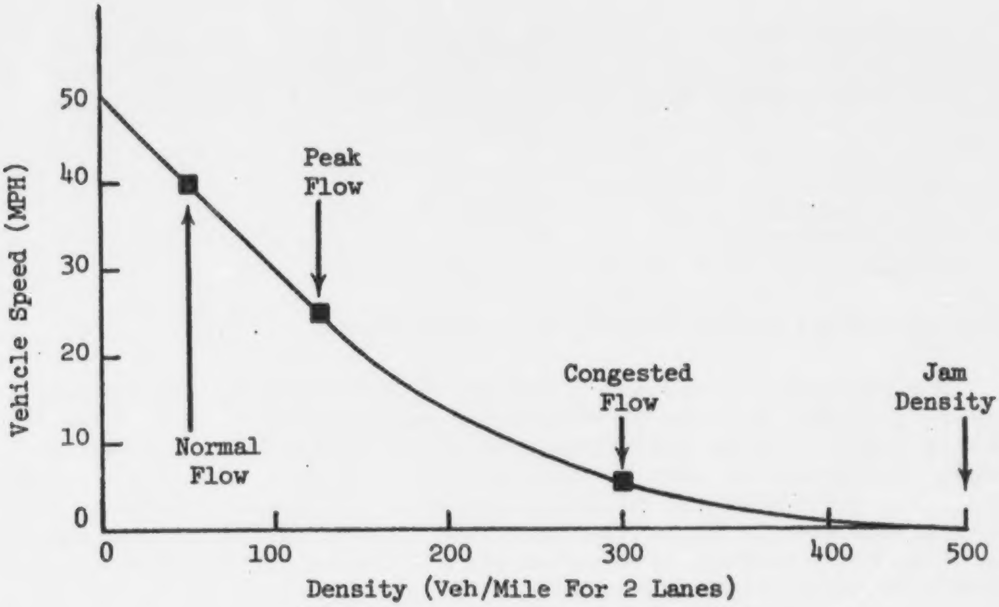
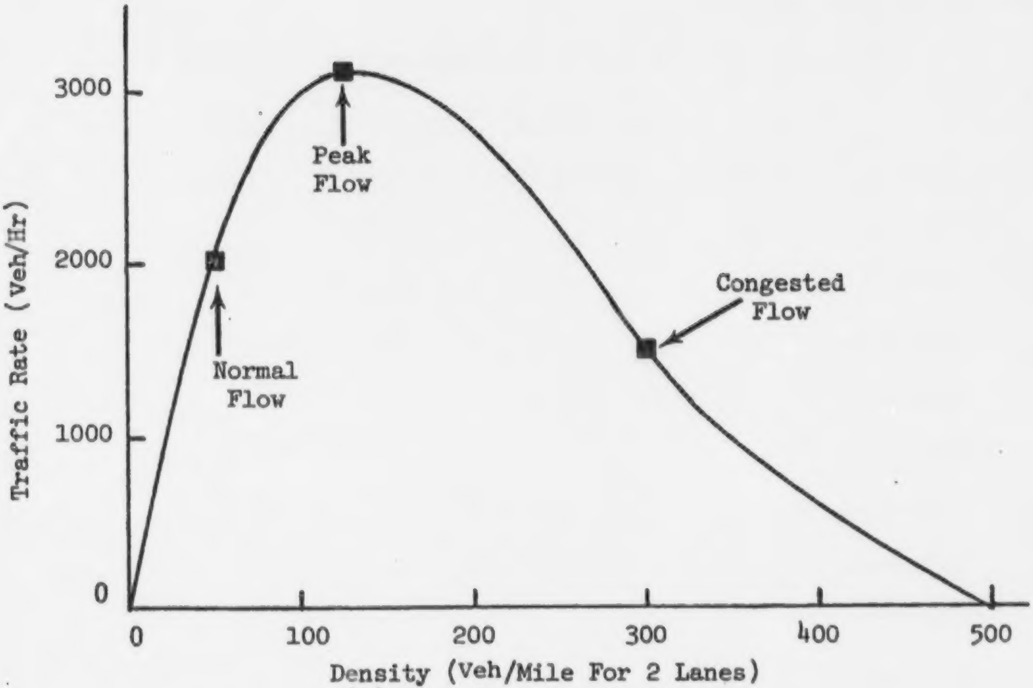


Figure 9. Average daily traffic distribution



(a) Average Speed Versus Density



(b) Flow Rate Versus Density

Figure 10. Relationships between traffic rate, vehicle speed and traffic density

Tunnel ventilation has been studied extensively, with Reference 22 providing an excellent survey of the entire subject. There are four principle tunnel ventilation systems used in the United States. They are:

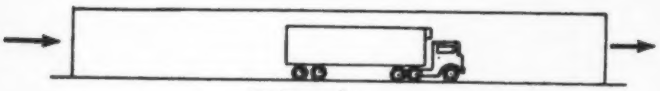
- Natural
- Longitudinal
- Semi-transverse
- Transverse

Figure 11 shows examples of each of these systems.

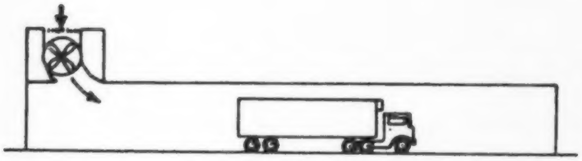
From Reference 22 and other sources, the distribution of commuter tunnels by length and type of ventilation was obtained for 41 of the 59 commuter tunnels. This distribution is shown in Table 7. In general, natural ventilation is used in tunnels under 1000 feet long, longitudinal ventilation for tunnels up to about 2000 feet long, semi-transverse in medium length tunnels up to 5000 feet, and transverse for tunnels longer than 5000 feet. Maximum ventilation rates for some U.S. tunnels are given in Table 8. The best way to compare ventilation between tunnels is to look at ventilation volume per second per meter of lane length. On this basis, the tunnels in Table 8 vary from a low of 0.073 m^3/sec per lane meter for the Brooklyn-Battery Tunnel to a high of 0.275 m^3/sec per lane meter for the Eisenhower tunnel in the Colorado Rocky Mountains. It should be pointed out that the Eisenhower tunnel was purposely designed with higher than usual ventilation capacity to account for the higher than normal CO emissions of vehicles at high altitude.

TABLE 7. COMMUTER TUNNEL VENTILATION TYPE BY TUNNEL LENGTH

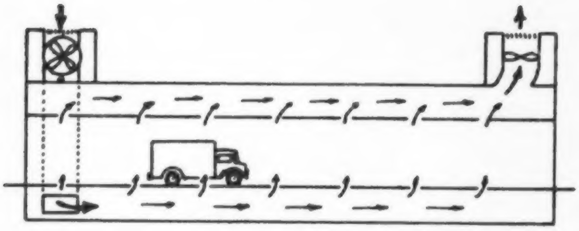
	Type of Ventilation				
Length	Natural	Longitudinal	Semi-Transverse	Transverse	Total
500-999	1	5	1		7
1000-1999	2	4	4	1	11
2000-2999		1	2	1	4
3000-3999			5	3	8
4000-4999			1	1	2
5000-5999		1		2	3
6000-6999				1	1
7000-7999				2	2
8000-8999				2	2
9000-9999				1	1
Total	3	11	13	14	41



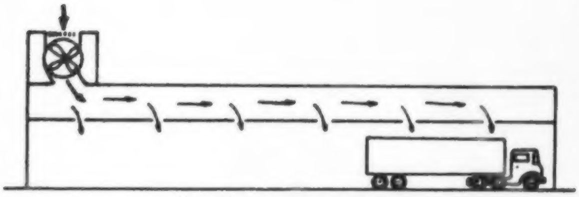
Natural



Longitudinal



Transverse



Semi-Transverse

Figure 11. Types of Tunnel Ventilation

TABLE 8. MAXIMUM VENTILATION RATES FOR SOME U. S. ROADWAY TUNNELS

Tunnel	Length, meters	No. of Tubes	Lanes/ Tube	Type of Vent.[a]	Vent. per tube m^3/sec	Vent./lane meter $(m^3/sec)/$ lane meter
Lowry Hill	456	2	3	S	252	0.184
Squirrel Hill	1288	2	2	S	275/175[b]	0.107/0.068[b]
Fort Pitt	1097	2	2	S	380	0.173
Bankhead	948	1	2	S	260	0.126
George Wallace	914	1	2	S	345	0.189
Baytown	917	1	2	S	425	0.232
			Average for semi-tranverse			0.154
Allegheny Mt.	1850	2	2	L	566	0.153
Caldecott #3	1027	1	2	T	232	0.113
Sumner	1724	1	2	T	289	0.084
Queens/Midtown	1933	2	2	T	330	0.085
Brooklyn-Battery	2779	2	2	T	405	0.073
Detroit-Windsor	1564	1	2	T	380	0.121
Baltimore Harbor	2332	2	2	T	357	0.077
Holland	2580	2	2	T	884	0.171
Lincoln	2408	3	2	T	839	0.174
Eisenhower	2725	2	2	T	1500	0.275
Thimble Shoals	1749	1	2	T	420	0.120
Hampton Roads	2280	1	2	T	400	0.088
			Average for transverse[c]			0.111

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[a] S = semi-transverse; L = longitudinal; T = transverse

[b] second number is for downhill tube

[c] excluding Eisenhower, which is greater because of tunnel altitude (11,000 ft)

Sources: (1) Schlang, R. N., et al. "Management of Air Quality In and Near Highway Tunnels, Interim Report," Federal Highway Administration Report FHWA-RD-78-184 January 1980.

(2) Rodgers, S. J., et al, "Tunnel Ventilation and Air Pollution Treatment," Federal Highway Administration Report FHWA-RD-72-15, June 1970.

(3) Personal Communication. P. L. Chandler, District Maintenance Engineer, District 5, Minnesota Department of Transportation to Melvin Ingalls, Southwest Research Institute, San Antonio, TX, dated August 28, 1980.

With the information presented above, the range of physical variables for the tunnel exposure situation are well defined. The typical tunnel exposure situation would be a 1000 to 2000 foot tunnel, with average daily traffic of between 10,000 and 15,000 vehicles per day. Ideally the ventilation system would be longitudinal or semi-transverse, with a ventilation rate close to 0.17 m^3/sec per lane meter. The severe exposure situation would be a tunnel over 5000 feet long, with ADT in excess of 15,000 vehicles per day. Tunnels of this length are generally transversely ventilated. If this is the case, it should have a ventilation rate less than 0.11 m^3/sec per lane meter.

The Lowry Hill tunnel in Minneapolis, Minnesota was chosen as the typical exposure situation. This tunnel has two tubes with three lanes per tube and is 456 meters (1496 ft) long. It has an ADT per lane of 12,000 vehicles. For commuter type tunnels this ADT per lane is about average. The ventilation is semi-transverse with a ventilation rate of 0.18 (m^3/sec)/lane meter. The ventilation rate and ADT were obtained from the District 5 Office of the Minnesota Department of Transportation. As shown in Table 7, the type of ventilation (semi-transverse) used in the Lowry Hill Tunnel is typical. The ventilation rate of 0.18 (m^3/sec)/lane meter is slightly higher than average for semi-transverse tunnels, as can be seen from examination of Table 8.

For the severe case, the Baltimore Harbor Tunnel was chosen, There are only three of the 59 commuter-type tunnels longer than the Baltimore Harbor Tunnel, making it one of the longest tunnels. Only five of the 29 commuter tunnels for which traffic counts were available had higher ADT/lane than this tunnel's ADT/lane of 16375 vehicles. The ventilation rate is also one of the lower rates for transversely ventilated tunnels, as shown in Table 8. Complete descriptions of both tunnels are included in Section V where the ambient concentrations for the tunnels are calculated.

D. Urban Expressways

The "MVMA Motor Vehicle Facts and Figures '80," lists the completed urban miles of the Interstate Highway System as 9678 miles.(70) Thus, there is no doubt that the expressway commuter exposure situation is important. To define the typical and severe exposure situations, the top 76 SMSA's in the 1970 census were investigated for expressway characteristics, ADT on various expressways, and climatic characteristics of the area. These 76 areas, with a 1970 population of 107.5 million, contained 53% of the 1970 U.S. population. The climatic data for the U.S. and most of the 76 SMSA's were obtained from the National Climatic Center in Asheville, NC.

The first step in defining typical and severe urban expressway exposures, is to define the number of miles of urban expressways. Table 9 lists the 1978 urban interstate mileage for each state. This information was taken from Table INT-11 of Reference 71. However, interstate highways are not the only urban expressways. In 1975 there were 8671 miles of urban interstate expressways and 6480 miles of other urban expressways.(72) In 1978 there were 9678 miles of urban interstate expressways.(71) Assuming the same percentage increase in other urban expressways, the 1978 mileage for this category would be 7232. This would bring the total estimated urban expressway mileage in the country in 1978 to 16,910 miles.

TABLE 9. URBAN INTERSTATE HIGHWAY SYSTEM MILEAGE

State	Miles of Urban Interstate	State	Miles of Urban Interstate
Alabama	202	Montana	37
Alaska	-	Nebraska	33
Arizona	151	Nevada	32
Arkansas	93	New Hampshire	45
California	864	New Jersey	258
Colorado	111	New Mexico	40
Connecticut	220	New York	534
Delaware	23	North Carolina	194
Dist. of Columbia	30	North Dakota	29
Florida	444	Ohio	656
Georgia	238	Oklahoma	138
Hawaii	34	Oregon	76
Idaho	45	Pennsylvania	339
Illinois	457	Rhode Island	67
Indiana	263	South Carolina	79
Iowa	138	South Dakota	21
Kansas	139	Tennessee	188
Kentucky	132	Texas	870
Louisiana	151	Utah	106
Maine	28	Vermont	7
Maryland	199	Virginia	241
Massachusetts	332	Washington	229
Michigan	426	West Virginia	71
Minnesota	165	Wisconsin	94
Mississippi	88	Wyoming	30
Missouri	291		
		Total	9,678 Miles

A joint frequency distribution of number of lanes and average daily traffic (ADT) would be ideal for determining expressway characteristics for the typical and severe exposure situation. However, after studying publications of the Federal Highway Administration (FHWA), and talking with personnel at FHWA, it was determined that useable joint frequency distributions do not exist. Here "useable" means one that defines number of lanes up to 10 or more total traffic lanes and ADT up to 200,000 vehicles or more. Joint frequency distributions listed in "Highway Statistics, 1978"(71) have the highest categories as: "4 or more lanes" and "40,000 or more vehicles"; thus placing almost all expressway miles in one category. Since joint frequency information was not available, separate distributions of expressway miles by number of lanes and by ADT were sought.

Information on miles of urban expressway by number of lanes was not available in sufficient detail from any of the FHWA publications. However, this information was retrieved from computer tapes of state highway statistics by the FHWA Highway Statistics Division for this project.(73) The printout was by state for 31 of the 50 states. Not all states were included because of differences in definitions and format of some reported statistics from some states. Unfortunately, many of the states for which information was not provided are states with large urban interstate mileages. To improve the completeness of the table, this information was obtained directly from the states of California and New York. Figure 12 is a histogram of the percent of urban interstate highway mileage by number of lanes for the 33 states for which information is available. Note that over half of the urban interstate highway mileage consists of four lane roadway.

Using just the interstate urban arterial figures from "Highway Statistics, 1978," the mean 1978 ADT for urban interstate arterials can be calculated as 47,664 vehicles. A complete distribution of the traffic volume is not available. However, a partial distribution for the urban interstate highway system is listed in Table INT-15 of "Highway Statistics, 1978." Figure 13 is a histogram of ADT taken from that table. As can be seen from the figure, the median ADT for the urban interstate system is between 30,000 and 40,000 vehicles. It is estimated that rush hour traffic counts are approximately nine percent of ADT counts.(74) The mean rush hour traffic is then about 4766 vehicles/hour.

From the above information on total miles of expressway and rush hour ADT, an estimate of the national total number of persons encountering a freeway exposure situation can be calculated. The average trip length is taken as 8.9 miles(70) with 5 miles of the trip on an expressway, and the average vehicle occupancy as 1.4 persons per vehicle for home-to-work traffic.(74) The number of persons exposed daily to rush hour expressway conditions in 1978 was approximately 22.6 million persons.

NOTE: For 33 states only. Does not include: Arizona, Connecticut, Dist. of Columbia, Florida, Georgia, Illinois, Kansas, Maryland, Massachusetts, Michigan, Missouri, New Hampshire, New Jersey, North Dakota, Oklahoma, Rhode Island and Wyoming.

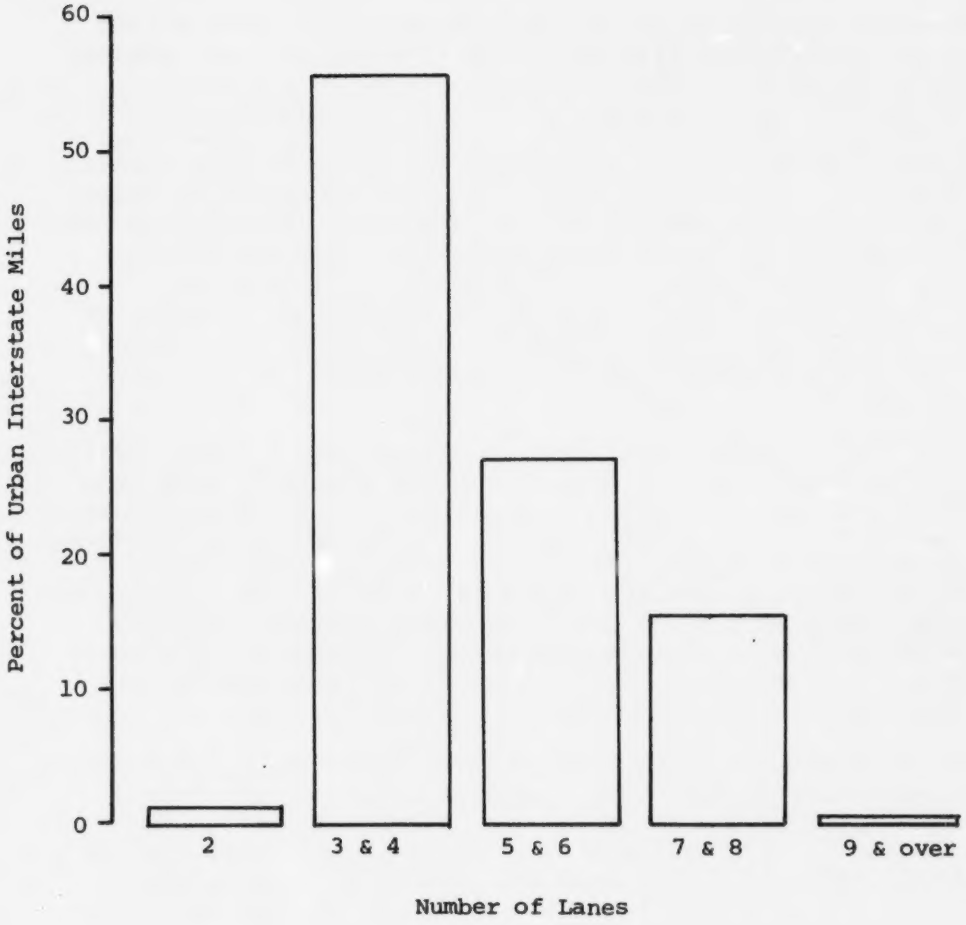

Figure 12. Urban interstate highway distribution by number of lanes

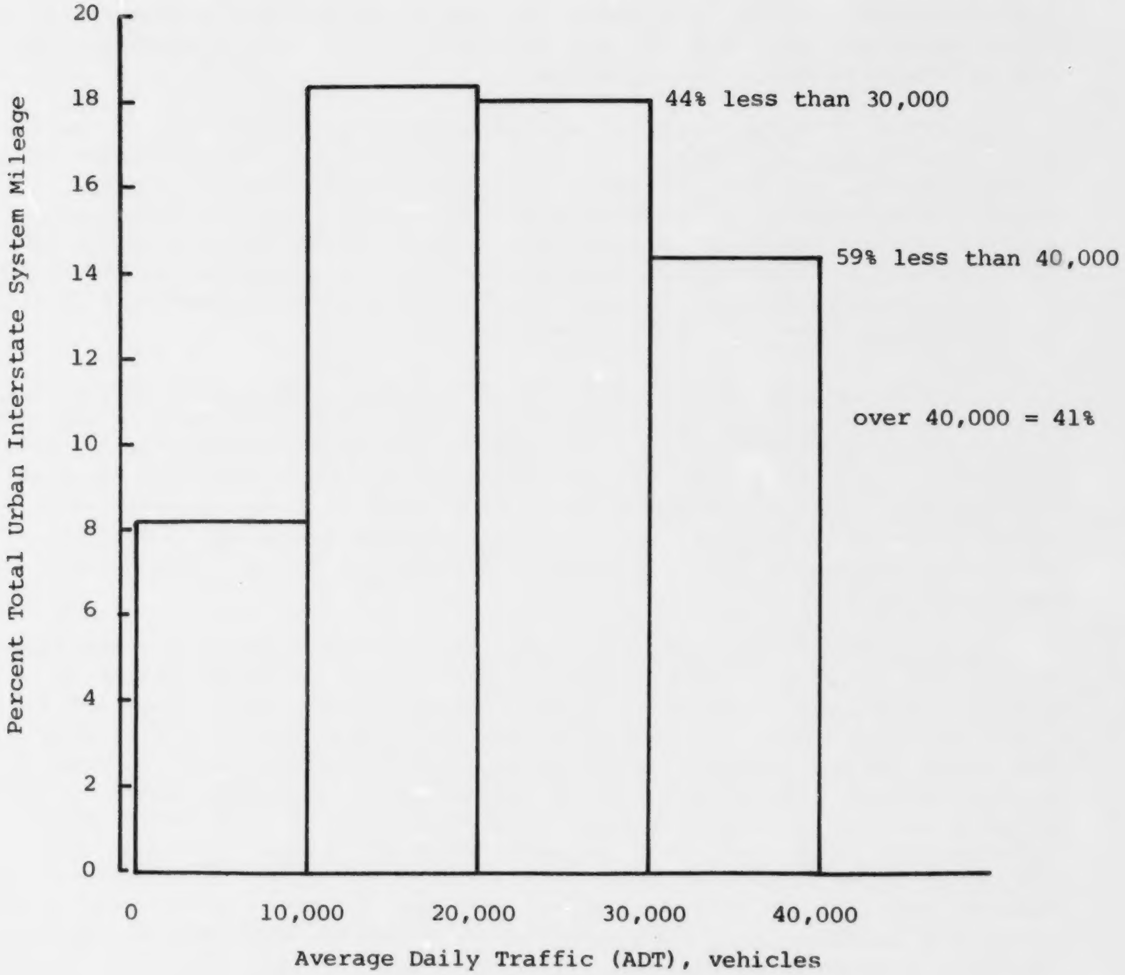

Figure 13. Average daily traffic distribution for the urban interstate system

No additional information on traffic count distribution was found. In an attempt to generate a better traffic count distribution, a computer listing of the annual average ADT from the FHWA permanent traffic count locations in all states was obtained from FHWA. Of the approximately 3500 locations, 362 were on urban interstate highways. How representative these locations are is unknown. In fact, of the 362 urban interstate locations, only 3 had ADT levels above 100,000 vehicles. A check of the 1978 Texas Traffic County Map, however, shows numerous locations in Houston, Dallas and San Antonio with ADT in excess of 100,000 vehicles. Since it appears that the permanent FHWA counter locations do not adequately represent the higher levels of ADT, this information was not used to determine the ADT distribution.

Some idea of maximum ADT for various numbers of lanes can be obtained by considering highway capacity. Expressway capacity is usually taken to be 1800 vehicles per lane per hour.(74) Rush hour traffic is generally around 9 percent of total daily traffic.(74) Using these two facts the capacity of expressways of various numbers of lanes are shown in Table 10. This information, together with the ADT distribution presented in Figure 13, provides enough information to determine the expressway characteristics for the typical and severe exposure situations.

Using Figures 12 and 13 and Table 10, a severe exposure situation would be one with an expressway of 10 lanes (5 in each direction) with an ADT of approximately 180,000 vehicles. The typical exposure siutation would be on a four lane expressway. The ADT for a typical exposure siutation is somewhat harder to define. However, if it is assumed that the distribution shown in Figure 13 is primarily for four lane expressways up to 40,000 vehicles, then Figure 13 can be used to determine a typical four lane expressway ADT.

The validity of the assumption that the ADT distribution for ADT less than 40,000 vehicles shown in Figure 13 can be used as the distribution on four lane expressway rests on several considerations. The maximum ADT for a four lane expressway is taken as 72,000 vehicles. Expressways greater than four lanes are not generally built unless the ADT for the desired "level of service" exceeds that of a four lane expressway. The highest level of service normally used is an hourly vehicle count equal to 0.35 times the highway capacity.(74) This means that few expressways of six or more lanes will have ADT levels below 38,000 vehicles. Thus, the 59 percent of Interstate mileage with ADT below 40,000 vehicles, shown in Figure 13, must include only a small percentage of expressways with more than four lanes. With this assumption, and with 55 percent of the total urban expressway mileage being four lanes, and 59 percent of the total urban expressway ADT being less than 40,000 vehicles, there can only be a small percentage of four lane expressway with ADT greater than 40,000 vehicles. Thus, the part of the total ADT distribution between 0 and 40,000 vehicles per day shown in Figure 13 can be used as the ADT distribution for four lane expressways. It appears then, that a typical ADT for a four lane expressway would be between 20,000 and 30,000 vehicles.

To completely define the expressway exposure situations, information on wind speed and direction is also required. Wind direction and speed distributions were investigated for 76 of the most populous standard metropolitan statistical areas (SMSA). While these distributions were sought for the rush hour time period of 7 to 8 a.m., only the wind speed distribution was found by time of day; wind direction distributions found included all hours of the day.(75,76)

TABLE 10. ESTIMATED CAPACITY OF URBAN INTERSTATE EXPRESSWAYS BY NUMBER OF LANES

Number of Lanes	Estimated Maximum Average Daily Traffic[a]
4	72,000
6	108,000
8	144,000
10	180,000
12	216,000

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[a] Estimated from data in Table 34 and Table 50, "Quick-Response Urban Travel Estimation Techniques and Transferable Parameters, Users Guide." National Cooperative Highway Research Program Report 187.

Annual wind direction distributions for all hours was available in the 16 compass point increments from either Reference 75 or Reference 76 for 62 of 76 SMSA. The prevailing wind direction and percent of time the wind is from that direction is shown in Table 11 for the 62 SMSA. There are 16 compass directions plus the category "calm" for a total of 17 possible wind direction categories. If there were an even distribution, each category would occur 5.9 percent of the time. In general, the prevailing wind direction occurs less than 20 percent of the time and, with the exception of Honolulu, never exceeds 25 percent.

In expressway exposure situations, it is the relative wind direction that is important. Thus, if a city had a prevailing wind a large percentage of the time, and had a large percentage of its expressway mileage in one direction, it could be possible to have a particular relative wind direction occuring on the expressway much more frequently than others. If this happened in a number of cities, it might be possible that there would be a relative wind direction on a national scale that occurs much more frequently than other directions.

To determine if this might happen, for those cities with a prevailing wind direction occuring a high percentage of the time, city expressway maps were visually inspected for a predominant expressway direction. No cities were observed to have a predominant direction for expressways. As a check to insure that the relative wind direction would be approximately equally distributed, the percent of total expressway miles for each relative wind direction was calculated in detail for San Antonio, Texas.

TABLE 11. PREVAILING WIND DIRECTION FOR SMSA OVER 400,000 POPULATION

	Direction	Percent Time
Akron, Ohio	S	12.4
Albany, N.Y.	WNW	15.2
Atlanta, Ga.	NW	14.7
Baltimore, Md.	WNW	11.0
Birmingham, Ala.	S	8.2
Boston, Mass.	SW	12.0
Buffalo, N.Y.	SW	15.0
Charlotte, N.C.	SW	9.3
Chicago, Ill.	SW	9.0
Cincinnati, Ohio	SSW	13.3
Cleveland, Ohio	S	15.0
Columbus, Ohio	SSW	9.1
Dallas, Tex. (Love Field)	S	16.0
Dayton, Ohio	S	12.3
Denver, Colo.	S	16.9
Detroit, Mich.	N	10.0
Fort Worth, Tex. (Dallas-Ft. Worth Regional)	S	21.3
Fresno, Calif.	NW	21.1
Grand Rapids, Mich.	SSW	12.8
Greensboro-Winston Salem-High Point, N. C.	SW	17.4
Harrisburg, Pa.	WNW	14.9
Honolulu, Hawaii	ENE	38.0
Houston, Tex.	SSE	14.0
Indianapolis, Ind.	SW	10.3
Jacksonville, Fla.	NW/SW	9.0
Kansas City, Mo-Kan.	SSW	12.3
Knoxville, Tenn.	NE	15.1
Los Angeles-Long Beach, Calif.	WSW	20.0
Louisville, Ky-Ind.	S	10.8
Memphis, Tenn.-Ark.	S	13
Miami, Fla.	ESE	11.0
Milwaukee, Wisc.	WNW	10.0
Minneapolis-St. Paul, Minn.	SE	9.6
Nashville, Tenn.	S	14.5
Newark, N.J.	SW	10.0
New Orleans, La.	S	9.0
New York, N.Y.	S	10.0
Norfolk-Va. Beach-Portsmouth, Va.	SW	11.6
Oklahoma City, Ok.	SSE	21.9
Omaha, Nebr-Iowa	SSE	18.8
Philadelphia, Pa.	WSW	11.0
Phoenix, Ariz.	E	15.2
Pittsburgh, Pa.	WSW	15.5
Portland, Ore-Wash.	NW	14.0
Providence-Warwick-Pawtucket. R.I.-Mass.	SW	10.8
Richmond, Va.	S	10.5

TABLE 11(Cont'd). PREVAILING WIND DIRECTION FOR SMSA OVER 400,000 POPULATION

	Direction	Percent Time
Rochester, N. Y.	WSW	15.4
Sacramento, Calif.	SW	15.0
St. Louis, Mo-Ill.	S	10.8
Salt Lake City, Utah	SSE	18.9
San Antonio, Texas	SSE	15.0
San Diego, Calif.	WNW	10.0
San Francisco-Oakland, Calif.	WNW/WNW	24.0/14.6
Seattle-Everett, Wash.	SW	13.0
Syracuse, N. Y.	WNW	11.7
Tacoma, Wash.	SSW	14.0
Tampa-St. Petersburg, Fla.	E	10.0
Toledo, Ohio	WSW	11.2
Tulsa, Okla.	S	18.6
Washington, D.C.	S	12.0
Wilmington, Del.	NW	11.2
Youngstown-Warren, Ohio	SW	12.2

For San Antonio, the complete wind direction distribution was used with the expressway direction distribution to obtain the percent of expressway miles with each relative wind direction. The expressway directions were expressed to the nearest compass point. If there were equal mileage in all directions, each direction would contain 6.25 percent of the expressway miles. For San Antonio, there is no one predominant expressway direction, although NE to SW and E to W expressways each have 20 percent of the total expressway mileage. The predominant wind direction in San Antonio is SSE occurring 15 percent of the time. The percent of expressway miles with each relative wind direction is shown in Table 12.

TABLE 12. DISTRIBUTION OF RELATIVE WIND DIRECTION FOR SAN ANTONIO, TEXAS, URBAN INTERSTATE EXPRESSWAYS

Wind Direction Relative To Expressway, Degrees	Percent Of Expressway Miles
0 and 180	12.30
22.5 and 202.5	9.87
45 and 225	11.19
67.5 and 247.5	11.59
90 and 270	13.29
112.5 and 292.5	12.60
135 and 315	13.50
157.5 and 337.5	12.56
Calm	3.00

If the expressway miles were equally distributed with respect to the relative wind direction, each direction (including "calm") would contain 11.1 percent of the mileage. The actual percentages shown in Table 12 do not vary enough from the 11.1 percent to use any particular relative wind direction as predominant. This conclusion has been extended to include the other cities in the U.S., by a comparison to San Antonio of their wind direction distributions and on a visual estimation of their expressway direction distribution. Thus, there is no one relative wind direction that can be called typical.

Wind speed is also needed to define the typical and severe expressway exposure situations. Since there is no one predominant relative wind direction, the wind speed distribution for all wind directions was used. The wind speed distribution with the largest number of speed intervals was found in the NOAA publication "Airport Climatological Summary".(76) This publication was available for 42 cities. Wind speed distribution is presented at three hour intervals. Unfortunately the data is taken at the same Greenwich Time for all stations, regardless of time zone. Thus, Eastern time zone cities have speed distributions at 7 a.m., Central time cities at 6 a.m., Mountain time cities at 8 a.m., and Pacific time cities again at 7 a.m.

The 7 a.m. data is probably the most representative of morning rush hour wind conditions. There were 25 cities with 7 a.m. data available; 20 Eastern cities and five West coast cities. This data was used to determine the average wind speed distribution. To obtain a wind speed distribution based on individual exposure, the speed distribution for each city was weighed by that city's percent of the total population for all 25 cities.

This population weighted wind distribition is shown in Figure 14 together with the unweighted minimum frequency, maximum frequency, and means for the various wind speed intervals. A wind speed of 6 knots (6.9 mph) would appear to be a typical speed, both from a median and mean standpoint.

With typical wind conditions defined, the typical expressway exposure situation can be defined as a four lane expressway with ADT of 20,000 to 30,000 vehicles and a wind speed of seven miles per hour, with all wind directions equally likely. The severe expressway exposure situation is a 10 lane expressway with ADT in excess of 180,000 vehicles. The most severe wind conditions are generally considered to be parallel wind, and wind speed as low as allowed by the dispersion model (about one m/sec., or 2.2 mph).

The typical exposure situation was chosen as IH 410 on the west side of San Antonio, Texas, between U.S. 90 and IH 35. This is a relatively straight, level, six mile section of four lane urban expressway, running in a NNW-SSE direction. The traffic count averages approximately 28,000 vehicles per day over the section to be modeled. It has the added advantage of being close to Southwest Research, so that traffic counts, grade, and dimensions could be easily checked.

The severe exposure situation was chosen as the Santa Monica Freeway in Los Angeles between the Harbor Freeway and IH 405, west of downtown. This is a relatively straight, level, 10 mile section of 10 lane freeway, running approximately in an east-west direction. The traffic count is approximately 200,000 vehicles per day. Complete descriptions of both section of expressway are included in Section V where ambient concentrations for both the typical and severe expressway situations are calculated.

E. Street Canyons

Street canyons, streets running between tall building, as occur sometimes block after block in the downtown section of large metropolitan areas, are yet another situation in which people are exposed to elevated levels of automotive pollutants. Ideally, information on the number of miles of street canyons by street width and canyon height-to-width ratio should be used to determine typical and severe exposure situation. However, no compilations of street canyon statistics (number of miles of street canyons, height-to-width ratios, etc.) were found.

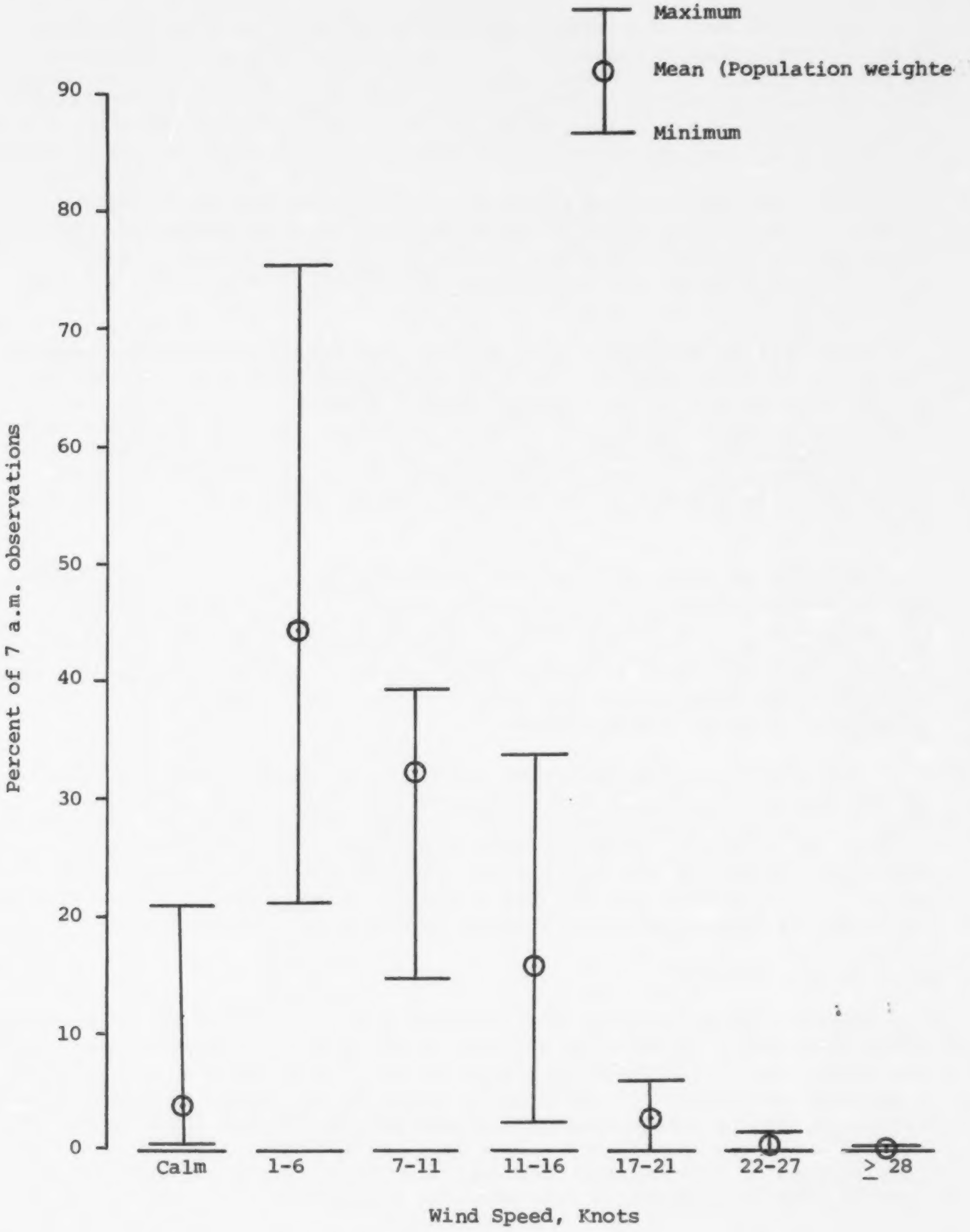


Figure 14. Wind speed distribution for 25 cities at 7 a.m.

A procedure to at least estimate the number of miles of street canyons was developed. It was to: (1) assume that all street canyons were in central business district (CBD); (2) obtain the CBD size for all SMSA's over 400,000 population (1970 census); and (3) assume a value for the number of street miles per square mile of CBD area. From these assumptions, the miles of streets in all CBD's was calculated. Assuming a certain average percentage of the CBD street miles were canyons, the total street canyon miles for all cities was obtained. This procedure gave the approximate national total, since few SMSA's under 400,000 population have any street canyons at all.

A search was made for information on central business district areas. It was found that the Bureau of Census has defined a CBD for each city over 100,000 population. The CBD area is generally defined in terms of a whole census tract or tracts. No compilation exists of the CBD areas(77), however, maps of each CBD are included in the Major Retail Center Statistics section of the 1972 Census of Retail Tracts.(78) Using these maps, the CBD area for 71 SMSA over 400,000 population was calculated. The total CBD area for the 71 SMSA's was 68.02 square miles. Table 13 lists the SMSA's and CBD areas.

The miles of street per square mile of CBD were calculated for six CBD of different size and type. The average was 19 miles of street per square mile of CBD. Using this average, the total miles of street in the 71 CBD's is 1292 miles. For all 76 SMSA over 400,000 pooulation, the total street mileage is 1383 miles.

To help determine the street canyon portion of this mileage, an aerial photograph of the CBD of Houston was obtained from a local aerial mapping company, United Aerial Mapping. (See Figure 15). From the photograph, it appears that approximately 30 percent of Houston CBD area could be considered street canyons.

It should be realized that Houston is a new, western style city. Older eastern cities probably have a greater portion of street canyons in the CBD. Some large city CBD's may even approach 100 percent street canyons. A 60 percent portion of the CBD mileage in street canyons will be assumed for this study. If 60 percent of the street mileage is in street canyons, there are approximately 830 miles of street canyons in the country.

Data on height to width ratios for street canyons are also nonexistent. Some idea of the possible range of street canyon height to width ratios can be obtained by looking at extremes of street width, building height, and wind speed. Wind speed is a necessary variable, since the street canyon dispersion model used is not good unless a helical air circulation is eatablished in the canyon. The establishment of a helical air circulation is dependent on windspeed, street width and building height.(33)

The wind speed and direction information collected for the expressway situation is also valid for the street canyon exposure situation. Since streets, like expressways, run in all directions, all relative wind directions are equally likely. The wind speed distribution during the morning rush hour used for expressways, shown in Figure 14, indicates that the wind speed is generally under 16 knots (18 mph, 8 meters/sec).

TABLE 13. CENTRAL BUSINESS DISTRICT AREAS FOR STANDARD METROPOLITAN STATISTICAL AREAS OVER 400,000 POPULATION (1970 CENSUS)

SMSA	1970 Population	CBD Area sq.mi.
Akron, OH	679,239	0.42
Albany-Schenectedy-Troy, NY	720,786	0.76
Allentown-Bethlehem-Easton, PA	543,551	0.40
Anaheim-Santa Ana-Garden Grove, CA	1,420,386	1.62
Atlanta, GA	1,390,164	1.39
Baltimore, MD	2,070,670	0.58
Birmingham, AL	739,274	0.15
Boston, MA	2,753,700	3.42
Buffalo, NY	1,349,211	0.65
Charlotte, NC	409,370	1.73
Chicago, IL	6,978,947	1.59
Cincinnati, OH	1,384,911	0.71
Cleveland, OH	2,064,194	1.11
Columbus, OH	916,228	0.82
Dallas, TX	1,555,950	1.44
Dayton, OH	850,266	0.81
Denver, CO	1,227,529	0.91
Detroit, MI	4,199,931	1.23
Flint, MI	496,658	1.38
Ft. Lauderdale-Hollywood, FL	620,100	0.18
Fort Worth, TX	762,086	0.93
Fresno, CA	413,053	0.28
Gary-Hammond-East Chicago, IN	633,367	0.94
Grand Rapids, MI	539,225	0.36
Greensboro-Winston Salem-High Point, NC	603,895	1.08
Hartford, CT	663,891	0.38
Honolulu, HI	630,528	0.19
Houston, TX	1,985,031	1.60
Indianapolis, IN	1,109,882	2.15
Jacksonville, FL	528,865	0.29
Jersey City, NJ	609,266	0.20
Kansas City, MO-KS	1,256,649	0.72
Knoxville, TN	400,337	0.61
Los Angeles-Long Beach, CA	7,032,075	2.82
Louisville, KY-IN	826,553	1.72

TABLE 13 (Cont'd). CENTRAL BUSINESS DISTRICT AREAS FOR STANDARD METROPOLITAN STATISTICAL AREAS OVER 400,000 POPULATION (1970 CENSUS)

SMSA	1970 Population	CBD Area sq.mi.
Memphis, TN-AR	770,120	0.48
Miami, FL	1,267,792	0.33
Milwaukee, WI	1,403,887	0.88
Minneapolis-St. Paul, MN	1,813,647	1.68
Nashville, TN	540,982	0.82
Newark, NJ	1,856,556	1.14
New Orleans, LA	1,046,470	1.28
New York, NY	11,528,649	3.75
Norfolk-Va. Beach-Portsmouth, VA	680,600	0.90
Oklahoma City, OK	640,889	0.28
Omaha, NB-IA	541,453	1.06
Paterson-Clifton-Passaic, NJ	1,358,794	0.24
Philadelphia, PA	4,817,914	1.65
Phoenix, AZ	968,487	1.00
Pittsburgh, PA	2,401,245	0.54
Portland, OR-WA	1,009,129	0.39
Providence-Warwick-Pawtucket, RI-MA	914,110	0.62
Richmond, VA	518,319	1.08
Riverside-San Bernardino-Ontario, CA	1,143,146	1.68
Rochester, NY	882,667	0.66
Sacramento, CA	800,592	0.22
St. Louis, MO-IL	2,363,017	0.33
Salt Lake City, UT	557,635	0.40
San Antonio, TX	864,014	1.07
San Diego, CA	1,357,854	0.32
San Francisco-Oakland, CA	3,109,519	1.66
San Jose, CA	1,064,714	1.33
Seattle-Everett, WA	1,421,869	0.48
Springfield-Chicopee-Holyoke, MA	529,922	0.22
Syracuse, NY	635,946	0.45
Tacoma, WA	411,027	0.31
Tampa-St. Petersburg, FL	1,012,594	1.36
Toledo, OH	792,571	0.46
Tulsa, OK	475,991	1.36
Washington, DC	2,861,123	1.51
Youngstown-Warren, OH	536,003	0.53

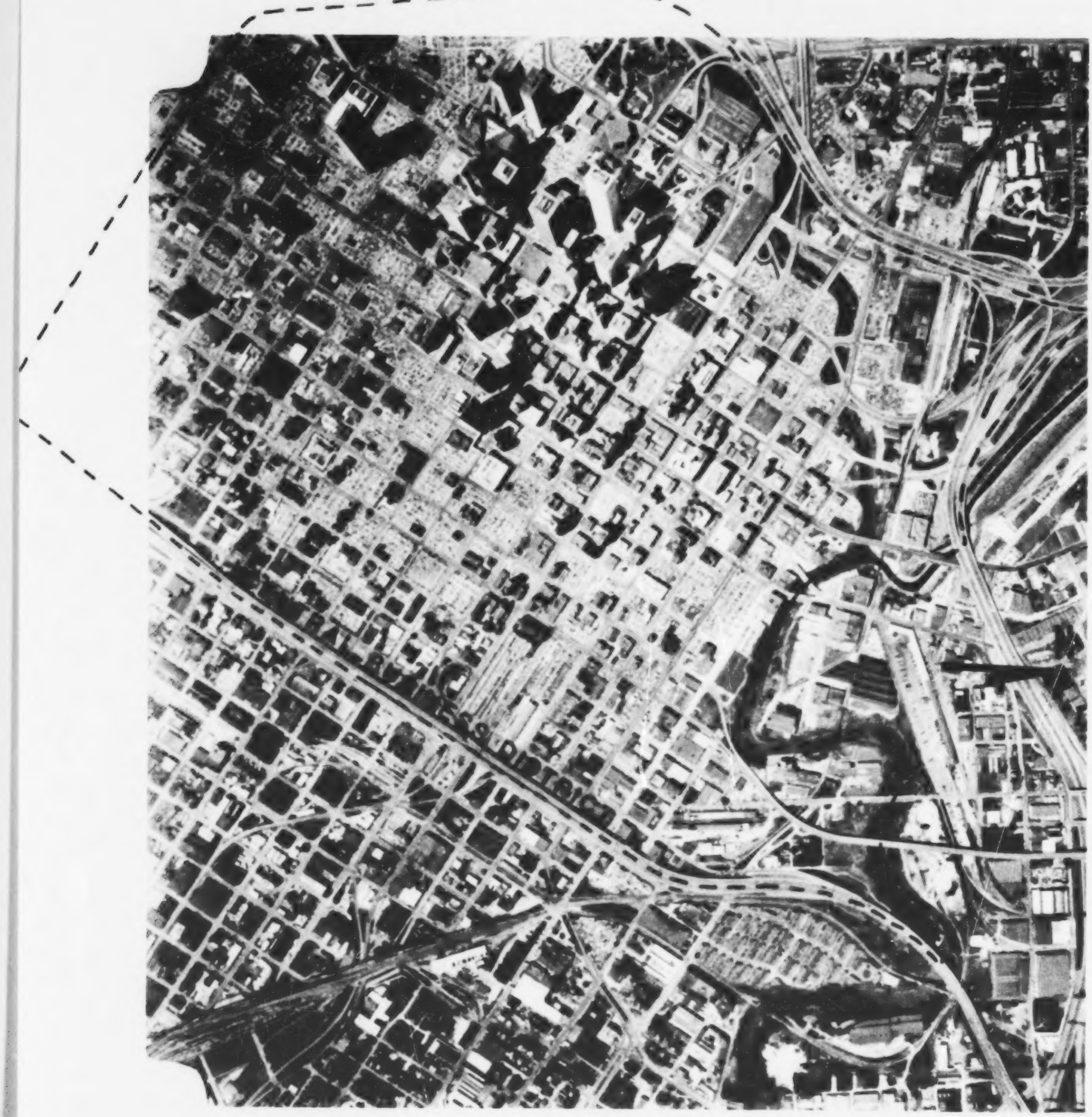

CENTRAL BUSINESS DISTRICT

Figure 15. Aerial View of Central Business District
Houston, Texas

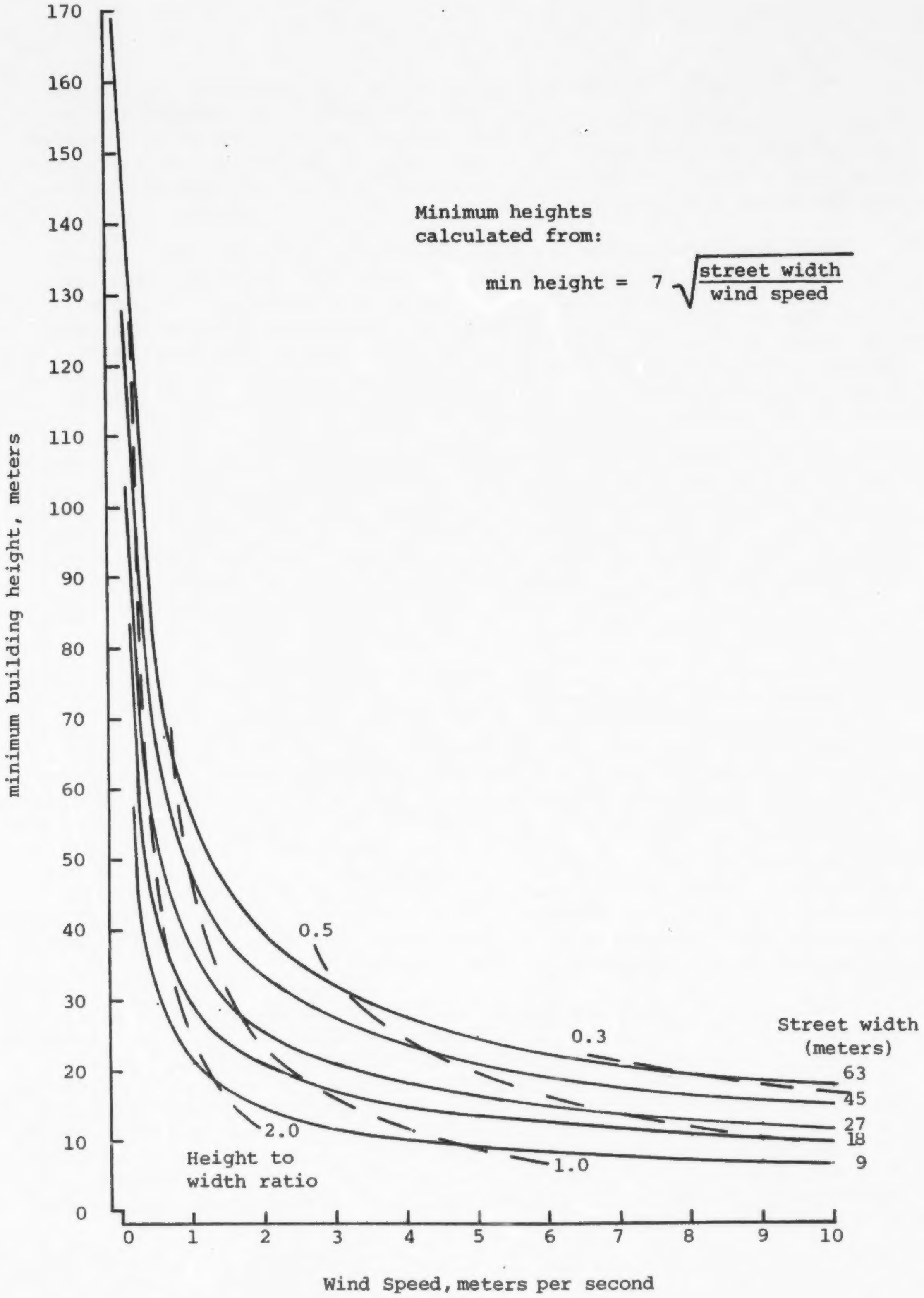
For this study, the minimum street width was assumed to be 9 meters (two 12 foot lanes, plus two three foot sidewalks). The maximum street width is assumed to be 63 meters (ten 13-foot lanes, three 12-foot medians and two 20-foot sidewalks). It is not known if there is actually a street this wide in existence, but it is judged to be a safe maximum assumption. Average street widths appear to be on the order of 20 meters.

Using the equation for the wind penetration depth from Reference 33 (See Section III), the minimum building height necessary for helical air circulation can be calculated for the range of wind speeds and street widths defined above. Figure 16 shows this minimum building height. Note from Figure 16 that for usual wind speeds, the minimum height to width ratio for helical flow must be above 0.3. Thus, 0.3 will be used as the minimum height-to-width ratio for a building-lined street to be defined as a street canyon.

For the narrowest street, the building height must be above 6.5 meters. This height is approximately two stories. Thus, street canyons must have buildings at least two stories high, even for the narrowest street. The highest buildings in the country are well over 1000 feet high. However, buildings over 300 feet (91 meters, about 26 stories) are considered "notable" by The World Almanac(52), which lists the notable tall buildings in major cities. Thus, it is probable that in most street canyons, buildings are under 91 meters in height.

Traffic counts for representative CBD streets were obtained from several sources.(79,80,81) These traffic counts are shown in Table 14. During peak traffic periods 1000 vehicles/hr for a CBD street would seem to be a good average for all SMSA over 400,000 population. Since the average CBD area is 0.96 square miles, it is not unreasonable to assume that each vehicle drives 0.5 miles through street canyons. One study has shown that 20 percent of the downtown vehicles are buses.(82) If it is assumed that each bus has 30 passengers and the remaining 80 percent of the vehicles are cars carrying 1.4 persons, then there are approximately 7 persons per vehicle in the CBD. Using these figures, approximately 11.6 million people in vehicles are exposed to CBD peak hour street canyon pollutant concentrations. Note that this figure does not include pedestrians who entered the canyon by another means (subways or on foot, for example).

While average daily traffic was used to obtain the number of persons exposed to street canyon concentrations, the traffic count is not sufficient to define typical and severe street canyon exposure situations. This is because the same number of vehicles per unit time can occur at two different speeds, as shown in Figure 17. Thus, a CBD street with low traffic counts can have a high traffic density traveling at a slow speed (congested traffic), or a low traffic density traveling at a higher speed (uncongested traffic). With stop and go driving, such as in encountered in city traffic, vehicle speed becomes an important consideration, since emissions can vary greatly with average cycle speed.



Minimum heights calculated from:

$$\text{min height} = 7\sqrt{\frac{\text{street width}}{\text{wind speed}}}$$

Figure 16. Minimum Building Height for Helical Air Circulation in a Street Canyon

TABLE 14. AVERAGE DAILY TRAFFIC FOR SOME CENTRAL BUSINESS DISTRICT STREETS IN SELECTED CITIES

City	Location	Daily Volume
Los Angeles, CA	Olympic west of Figueroa	28,662
Los Angeles, CA	1st Street east of Los Angeles St.	18,418
Los Angeles, CA	Figueroa south of Pico	20,282
Los Angeles, CA	Figueroa at 11th Street	23,394
Houston, TX	Milam south of Pease	18,183
Houston, TX	Main north of Pease	15,608
Houston, TX	Louisiana north of McKinney	18,965
San Antonio, TX	Houston Street, east of St. Mary's	15,293
New York City, NY	Lexington between 45 and 46th St	~18,000

Notes:

1. Los Angeles data from "Traffic Counts 1979" City of Los Angeles Department of Transportation.
2. Houston data from "City of Houston, Traffic and Transportation Department, Traffic Volume Summary as of 03-23-79."
3. San Antonio data from San Antonio Traffic and Transportation Department.
4. New York City data taken from: "Effect of New York City Taxi Strike on CO Concentrations in Midtown Manhattan." APCA Journal Vol. 29, No. 8. August 1979.

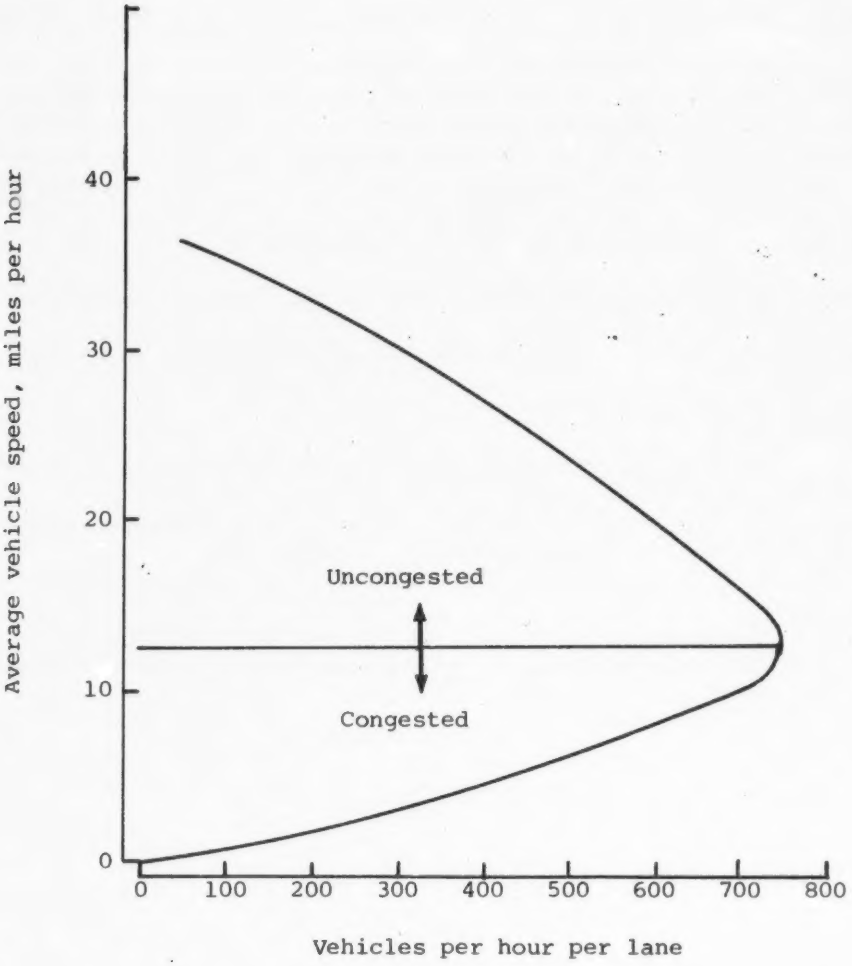


Figure 17. Example of traffic speed relationship to traffic flow

Just how emissions vary with speed is dependent on the pollutant. Figures 18 and 19 show regulated and unregulated emission levels from four different cars operated on four different urban driving cycles, as a function of the average speed of each cycle.(83) As can be seen from the figures, there is no single trend. Some emissions increase with increasing vehicle speed, some decrease. Thus, it is difficult to say whether 1000 vehicles per hour traveling at five miles per hour (congested traffic) or 2000 vehicles per hour traveling at 20 miles per hour (uncongested traffic) would be the more severe case from an air pollution standpoint.

These facts indicate that two different traffic flows should be considered for each street canyon situation. One flow should be of congested traffic (low flow, low speed) another of uncongested traffic (higher flow, higher speed). While this conclusion is a departure from the strict "real world situation" philosophy of this project, it is necessary to allow assessment of the effects of a variety of unregulated pollutants in a street canyon situation. From an examination of a variety of traffic flow data and information, it appears that 200 vehicles per hour per lane at five miles per hour would be a good representation of congested flow; while 400 vehicles per hour per lane at 20 mph would be a good representation of uncongested flow. These traffic flows will be used with both the typical and severe street canyon situations.

It should be obvious from the above discussion that it will not be possible to define typical and severe street canyon exposure situations with any degree of certainty. In addition, the height to width limitation of 2.0 imposed on the model means that the truly severe exposure situation (wind speed lower than 0.5 m/sec, or building height above 91 meters) can not be modeled. Therefore, the street canyon locations were chosen on a subjective basis keeping in mind the range of variables possible.

The typical location was chosen as Houston Street between Navarro and St. Mary's in downtown San Antonio, Texas. This is a four lane, one-way street with seven foot wide sidewalks on both sides. The total width of the street and sidewalks is 18.6 m (61 feet). The average leeward side building height (assuming southerly winds) is 33.7 m (111feet). The height to width ratio is then 1.81. The typical wind speed of 3.13 m/sec (7 miles/hr) will be used. The ADT for Houston Street at this location is approximately 15,300 vehicles per day.

Since the model limited the canyon height to width ratio to 2.0, the severe case was chosen on the basis of number of traffic lanes and traffic counts, plus the more practical consideration of availability of the necessary information. A local aerial mapping company had stereographic aerial photographs of the Houston area from which building heights could be determined. Since downtown Houston streets are in general six-lane one-way streets with heavy traffic, a street canyon in Houston appeared to be a good location for the severe exposure case. Care had to be taken to insure that a street canyon with less than 2.0 height to width ratio was chosen.

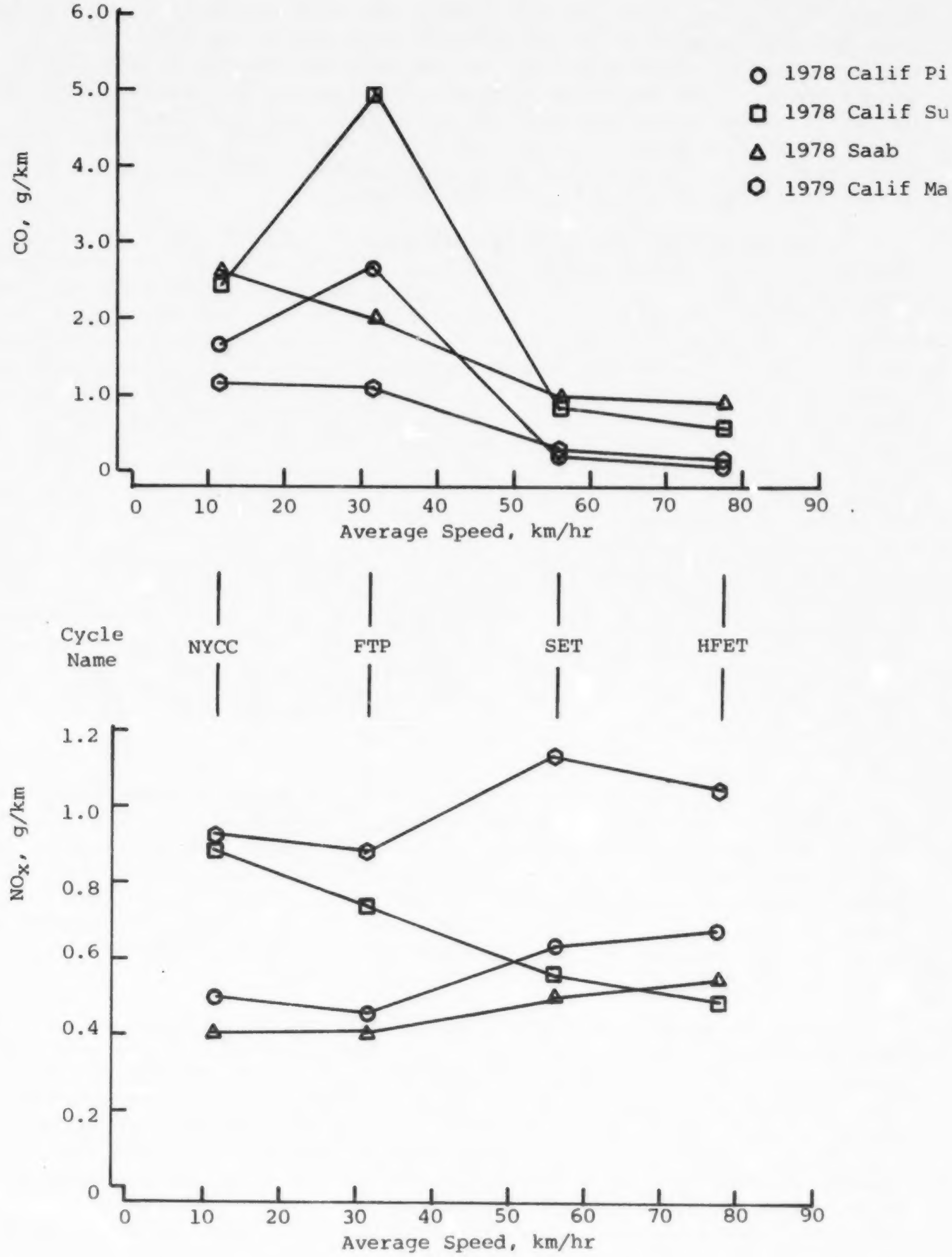


Figure 18. Effect of driving cycle speed on NO_x and CO Emissions

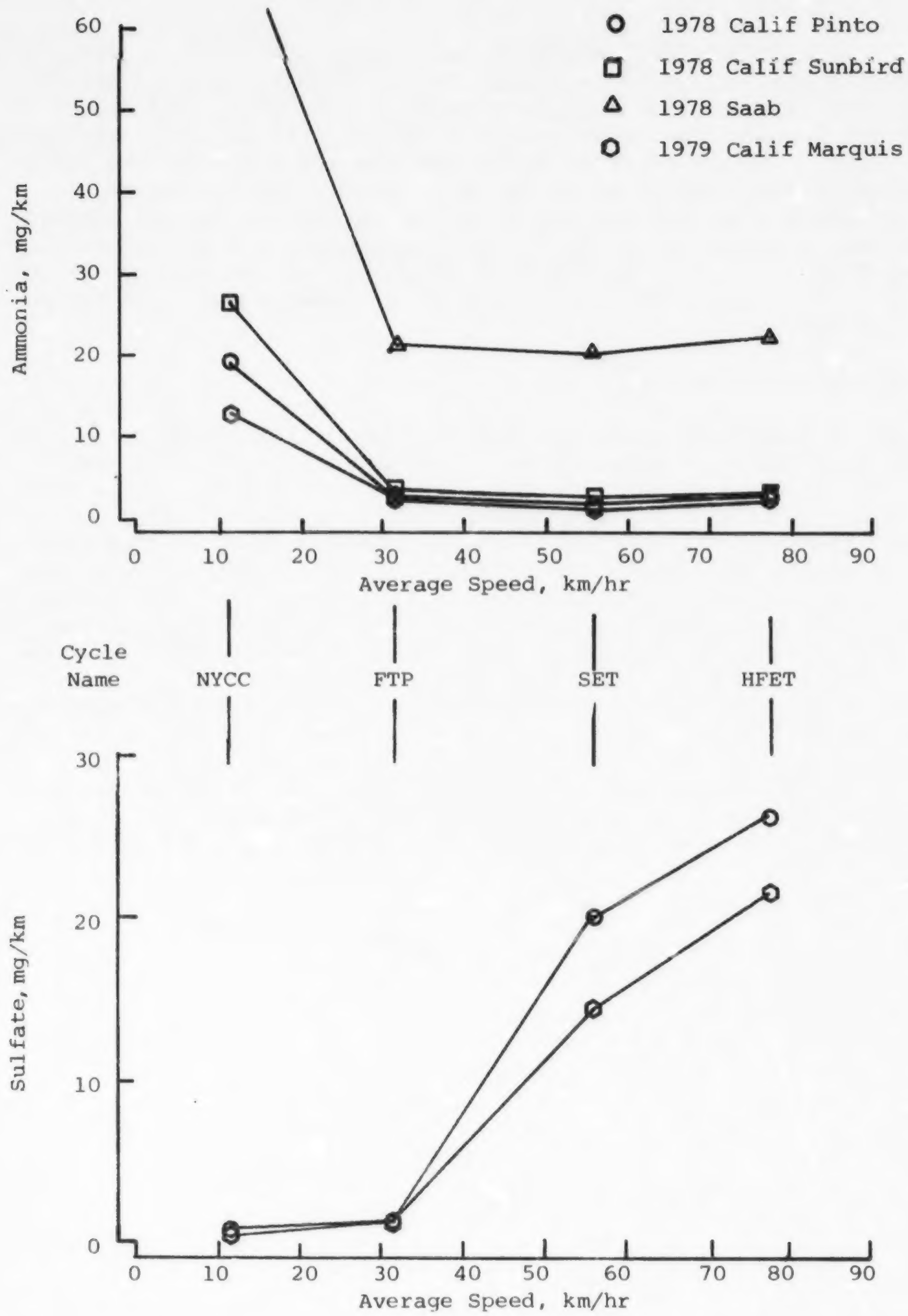


Figure 19. Effect of driving cycle speed on ammonia and sulfate emissions

The final section was Main Street, which runs NE to SW, between Capitol and Rusks streets. The building height on the southeast side of the block (leeward side) average 38 m (125 feet) above street level. The street is 27 m (90 feet) wide. The canyon height to width ratio is 1.39. The average traffic count is on the order of 20,000 vehicles per day. For the severe case, the wind speed should be as low as possible. From Figure 16, for a street 27 meters wide, the building height of 38 meters, the minimum wind speed to have a helical flow pattern is approximately 0.9 meters/sec (2.1 miles per hour). Complete descriptions of the two street canyons are included in Section V with the calculation of the ambient pollutant concentrations in each canyon.

F. Localized Area Sources

Since no dispersion model was found for predicting concentrations within an area source, a much smaller effort was allotted to the investigation of the range of physical variables of area sources. There have been a number of studies of individual parking lots(94,95,96,97), but none have attempted to define the magnitude of the problem on a national scale. No studies were found on such area sources as trucking terminals, warehouses or similar situations. From the data presented in Reference 57, it is estimated that there are at least 60,000 privately-owned and municipal parking lots open to the general public. The average lot has 66 parking spaces. However, parking lots can be many times the average size. For instance, the Oakbrook Shopping Center in suburban Chicago has a parking lot capacity of 7,200 spaces.(94)

Since there is no dispersion model for this expsoure situation, no typical or severe location was chosen. However, the ambient CO concentration measured in three large parking lots will be discussed in Section V.

V. AMBIENT CONCENTRATIONS FOR SELECTED EXPOSURE SITUATIONS

In this section, the models selected in Section III are applied to the real world typical and severe situations selected in Section IV. The emission factor used was one gram per mile per vehicle, or one gram per minute per vehicle, as appropriate.

Ambient concentrations for any pollutant may be obtained from the calculated concentrations presented here, simply by multiplying the concentration by the new pollutant emission factor in grams per mile or grams per minute as appropriate. To demonstrate this procedure, the ambient concentration CO was determined for each situation. Where possible, the CO level was compared to measured CO concentrations for the same or a similar location. The CO emission factor used for computation varied with the calendar year for which the comparison was made, location (whether in California or another state), and average vehicle speeds. In every case, an attempt was made to use the most realistic CO emission factor available.

A. Residential Garage Concentration

The typical and severe residential garage exposure cases selected in Section IV use the same physical setting, but different pollutant generation times. An illustration of the garage is shown in Figure 20.

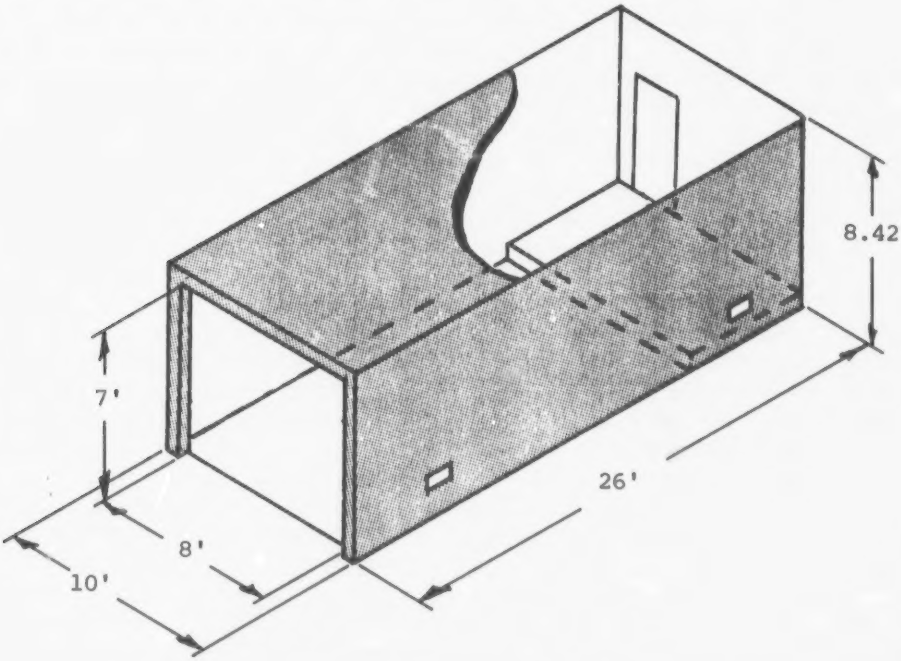


Figure 20. Single car garage with storage space

All walls and ceiling are finished. There are two free air vents with a combined open area of 288 in^2. An "overhead door" is provided for auto access. A weather stripped door is provided for garage-interior access, and is assumed to be effectively "sealed." The volume of the garage is 2189 cubic feet (10x26x8.42). The volume of vehicle and appliances have not been subtracted from the total volume.

Since there is no mechanical ventilation in a residential garage, all ventilation is the result of infiltration and natural ventilation. Infiltration pertains to ventilation due to wall leakage and window leakage. Natural ventilation pertains to ventilation by intentional openings, such as windows or vents. From the ASHRAE handbook, a room with no windows or exterior doors would have an effective room air change every two hours. The air for the room air change comes from air infiltration through the walls, caused by a differential pressure between the interior and exterior spaces, and it depends on ambient conditions of wind and temperature.(84)

The main source of infiltration for the garage is the garage door. The door has a sealing perimeter of 30 feet with a loose fit to enable it to slide. It is assumed that the infiltration is similar to a wooden double hung window which is not weatherstripped. Assuming a Δp of 0.1 in. H_2O, corresponding to a fairly low wind velocity and only a minor temperature difference, the infiltration would range from about 27 cfh to 53 cfh per foot of crack for cracks 0.047 to 0.094 inches wide, respectively. Picking 40 cfh per foot of crack yields 1200 cfh (20 cfm), or a change of garage air every 1.8 hours.(89) This 20 cfm of air infiltration would pass through the 2 square feet of free air vents with a velocity about 2 in/sec, which seems reasonable. The ventilation for the garage with the door closed is taken to be 20 cfm.

Natural ventilation for the residential garage would be primarily due to opening the garage door in conjunction with the free air vents. The garage door represents almost one of four walls and has an opening area of 56 ft^2. Assuming an 88 ft/min wind velocity, V, and an effectiveness, E, of about 0.3 due to the wind direction being skewed to the plane to the door, the natural ventilation through the 56 ft^2 doorway would be 1478 ft^3/min. Flow rate is defined as: cfm - Effectiveness x Wind Velocity (ft/min) x Area (ft^2). Applying these same assumptions to the free open vent area of 2 ft^2, natural ventilation through the vents would be 52.8 ft^3/min.

With an "inlet" of 56 ft^2 (garage door) and outlet of 2 ft^2 (free open vents), ASHRAE recommends taking the flow rate through the smaller opening and adding a portion of the flowrate from the larger opening.(84) Based on the ratio of inlet to outlet areas, this is 52.8 ft^3/min from the vents plus 38 percent of the 1478 ft^3/min from the garage door opening. This gives a ventilation rate of 615 ft^3/min which corresponds to 16.8 changes per hour, or a room change every 3.57 minutes with the garage door open. The velocity of this ventilation air through the garage doorway would be 11 ft/min. The ventilation for the garage with the door open is thus taken to be 615 cfm.

1. Application of the Enclosed Space Model

Since both the typical and severe exposures occur while the room concentrations are increasing rapidly it is necessary to consider the concentrations as a function of time. Each of the three components of the enclosed space model set forth in Section II will be calculated separately and plotted as a function of time. Aside from the physical variables of the garage described on the previous page, several other parameters are required. To calculate the contribution of the initial concentration, it is assumed that sufficient time has passed to allow the room concentraion to reach ambient concentration. Initial concentration corresponds to C_o in the model equation for C_1. A unit concentration of 1 $\mu g/m^3$ is assumed. The emission rate is used in the model equation for C_3. A unit emission rate of 1 gram/min is assumed.

As mentioned in Section II, the effective ventilation factor is difficult to assess, and little information as to its value has been found. Considering the definition of the ventilation factor can help to estimate a value for these situations. Recall from Section III, that the ventilation factor is less than 1.0 if the ventilation system removes less pollutant than would be removed if the pollutant were distributed homogeneously. In this situation, with little air movement within the garage it is probable that much less of the generated pollutant is removed per unit time than would be removed if it were distributed homogeneously. Therefore, an effective ventilation factor for the generated pollutant (C_3 equation) of 0.25 has been assumed. For the equations for initial concentration decay (C_1 equation) and for the incoming ventilation concentration (C_2 equation), the effective ventilation factor has been assumed to be 1.0; since the pollutant is nearly homogeneously distributed in both cases.

Figures 21 and 22 contain the curves of concentration as a function of time for the three components of the enclosed space model; initial concentration decay (C_1), inlet ventilation concentration (C_2), and generated pollutant concentration (C_3).

2. Typical Residential Garage Concentrations

For the typical exposure situation, the receptor enters the garage from the house, opens the overhead door, starts the car and allows 30 seconds to warm-up at fast idle. He then backs the car out of the garage, closes the overhead door and drives off.

The maximum concentration to which the receptor is exposed occurs at 30 seconds after the engine was started. To use Figures 21 and 22, the engine starting time is taken as time zero. At time 30 seconds the three model components obtained by reading each curve at t = 0.5 minutes are:

C_1 = 0.870 $\mu g/m^3$

C_2 = 0.132 $\mu g/m^3$

C_3 = 7900 $\mu g/m^3$

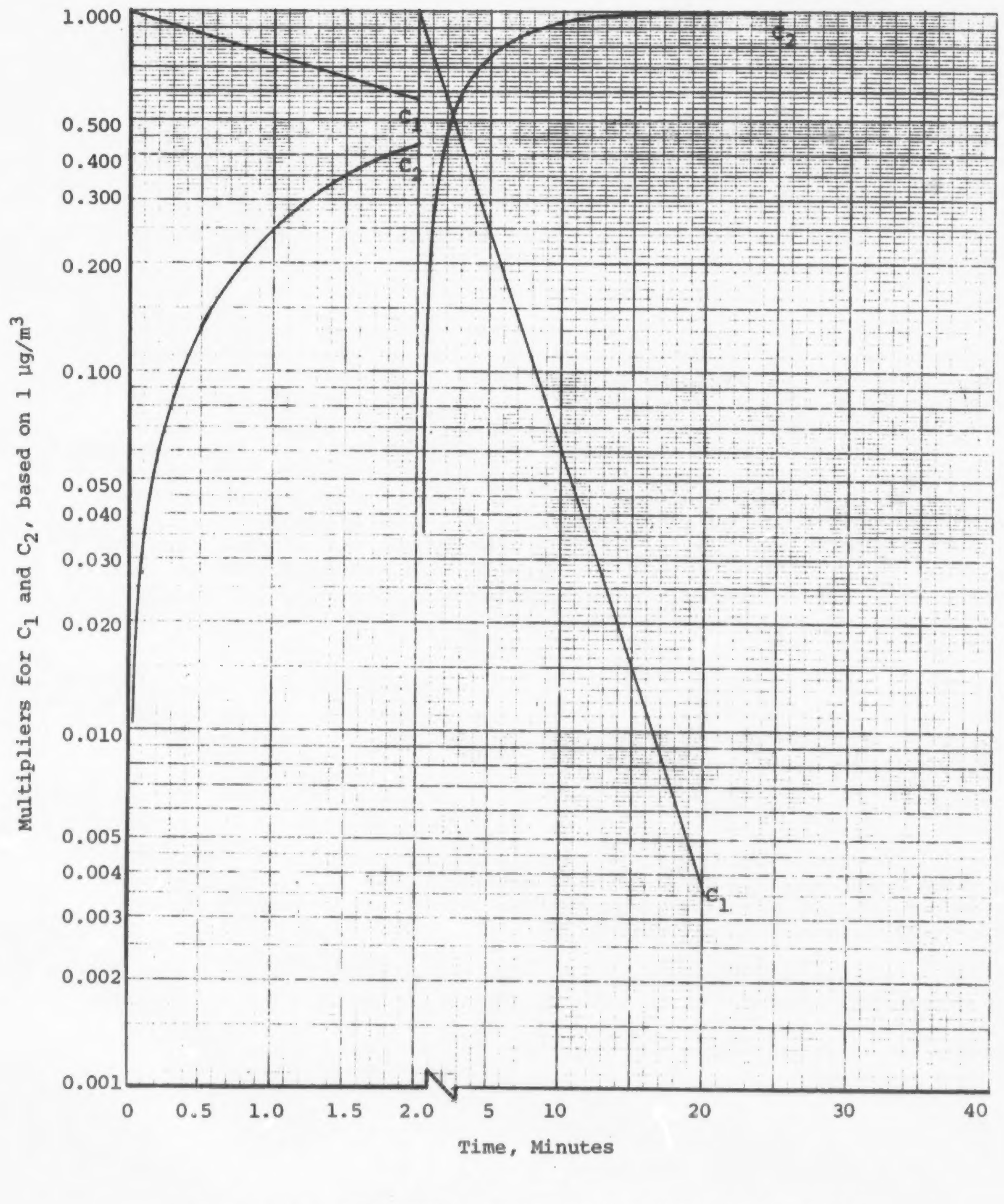


Figure 21. Residential garage multipliers for C_1 and C_2

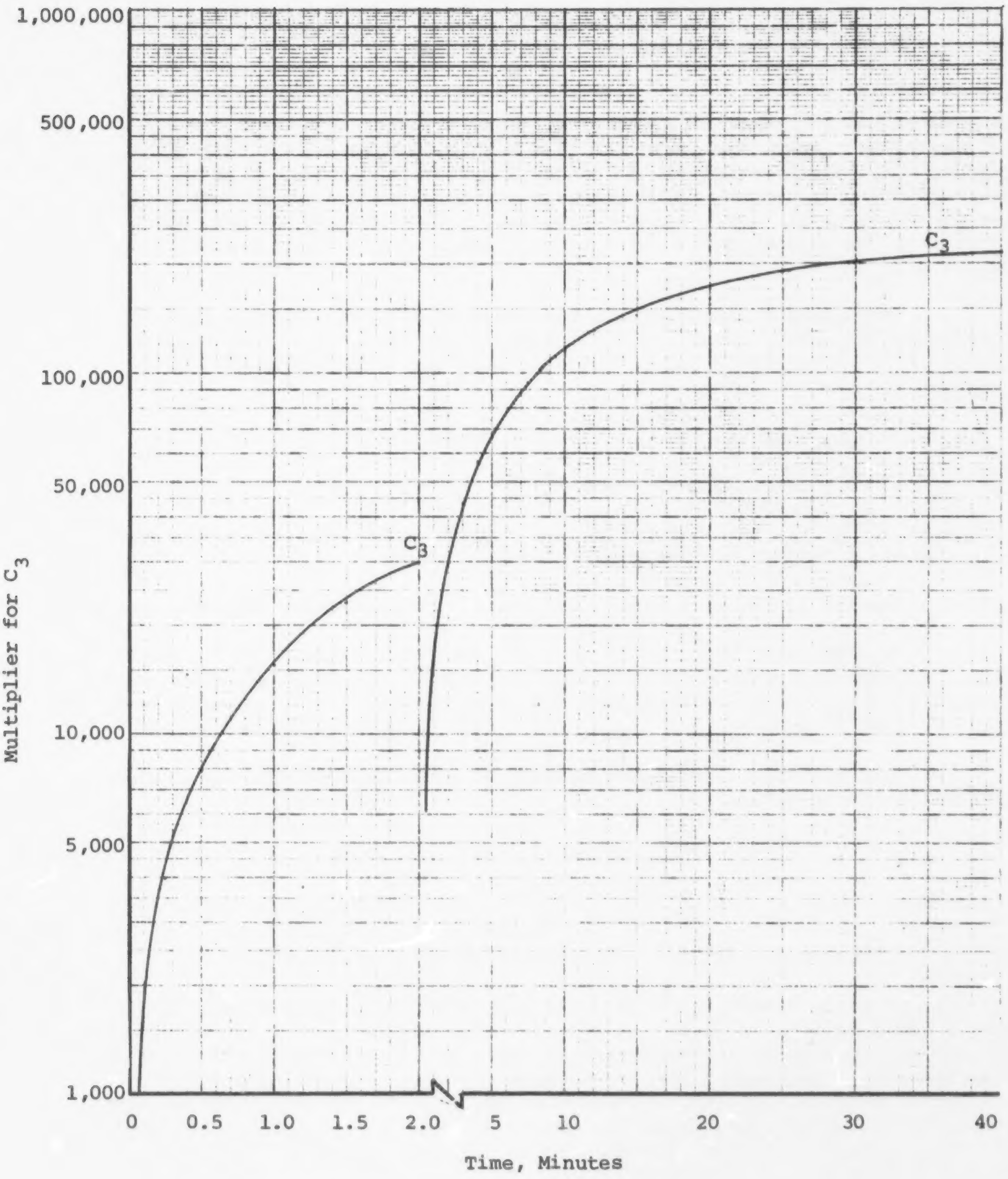


Figure 22. Residential garage multiplier for C_3

A summary of the physical parameters and concentrations for the typical case is given in Table 15 following the presentation of the severe case.

3. Severe Residential Garage Concentrations

For the severe exposure situation, the pollutant generation time is greater, and the receptor spends more time in garage after the car is started. The severe case assumes a cold winter morning with an unheated garage. The receptor enters the garage from the house entrance, opens the overhead door, starts the car, and returns to the inside of the house while the car warms up at idle. After approximately five minutes, the receptor returns to the garage, backs out the car, closes the overhead door and drives off.

The maximum concentration the receptor will be exposed to in this case occurs five minutes after the engine was started. From Figures 21 and 22, at time five minutes, the values of the three components are:

$$C_1 = 0.242\ \mu g/m^3$$

$$C_2 = 0.750\ \mu g/m^3$$

$$C_3 = 67000\ \mu g/m^3$$

A summary of the physical parameters and concentrations for the severe case is presented in Table 15.

4. Use of Residential Garage Concentrations with Other Emission Factors

To use these values with other pollutants, multiply C_1, C_2 and C_3 by the appropriate concentration or emission factor then sum the three new concentrations. For example, assume that the cold-start CO generation rate for the first 30 seconds is 8 g/min, and the CO background is 3000 $\mu g/m^3$.

For the typical exposure situation, after 30 seconds, the CO concentration in the garage is:

$$\begin{aligned} C_1 &= 0.870 \times 3000 = & 2{,}610\ \mu g/m^3 \\ C_2 &= 0.132 \times 3000 = & 396\ \mu g/m^3 \\ C_3 &= 7900 \times 7 \quad = & \underline{63{,}200\ \mu g/m^3} \\ \text{Total concentration} &= & 66{,}206\ \mu g/m^3 \text{ or } 57.6 \text{ ppm CO} \end{aligned}$$

For the severe exposure situation, assume that the CO rate drops from 8 g/min to 5 g/min at $t = 30$ seconds. To calculate the CO concentration for the severe case, it is necessary to redesignate the time at which the CO generation rate changed as $t = 0$. In this case, it is 30 seconds after the engine started. C_o is now total concentration in the garage 30 seconds after the engine started, or 66,206 $\mu g/m^3$. C_i has not changed. The time at which to enter the graph for the severe case (five minutes after engine start) is then $t = 4.5$ minutes.

TABLE 15. AMBIENT CONCENTRATIONS FOR RECEPTOR IN RESIDENTIAL GARAGE - TYPICAL AND SEVERE CASES

	Typical Case	Severe Case
Garage Volume, cubic feet	2189	2189
Ventilation rate (door open) cfm	615	615
Initial concentration, $\mu g/m^3$	1.0	1.0
Intake air concentration, $\mu g/m^3$	1.0	1.0
Emission factor, g/min	1.0	1.0
Ventilation factor, initial conc.	1.0	1.0
Ventilation factor, intake air	1.0	1.0
Ventilation factor, exhaust emissions	0.25	0.25
Time after start of engine, minutes	0.5	5.0
Concentrations:		
C_1, contribution of initial conc. $\mu g/m^3$	0.870	0.242
C_2, contribution of intake conc. $\mu g/m^3$	0.132	0.750
C_3, contribution of exhaust emissions, $\mu g/m^3$	7900	67000

$$C_1 = 0.290 \times 66{,}206 = 19{,}200\ \mu g/m^3$$
$$C_2 = 0.720 \times 3{,}000 = 2{,}160\ \mu g/m^3$$
$$C_3 = 60{,}000 \times 5 = \underline{300{,}000}\ \mu g/m^3$$
$$\text{Total Concentration} = 321{,}360\ \mu g/m^3 \text{ or } 279 \text{ ppm CO}$$

Note that in this case, it was not possible just to take the concentrations at 5 minutes and multiply by the emission factor. Because the emission factor changed, it was necessary to use the graphs and work the problem in two parts.

No CO measurements within a residential garage were found in the literature. One study did show CO measurements in a room next to an attached garage.(85) In that study, the CO increased from 1 ppm before the car was removed to 5 ppm after the car was taken from the garage. This situation was apparently similar to the typical situation presented here. It does not seem unreasonable that the CO concentration inside should increase by a factor of 5 while the garage CO concentration increased by a factor of 20.

B. Parking Garage Concentrations

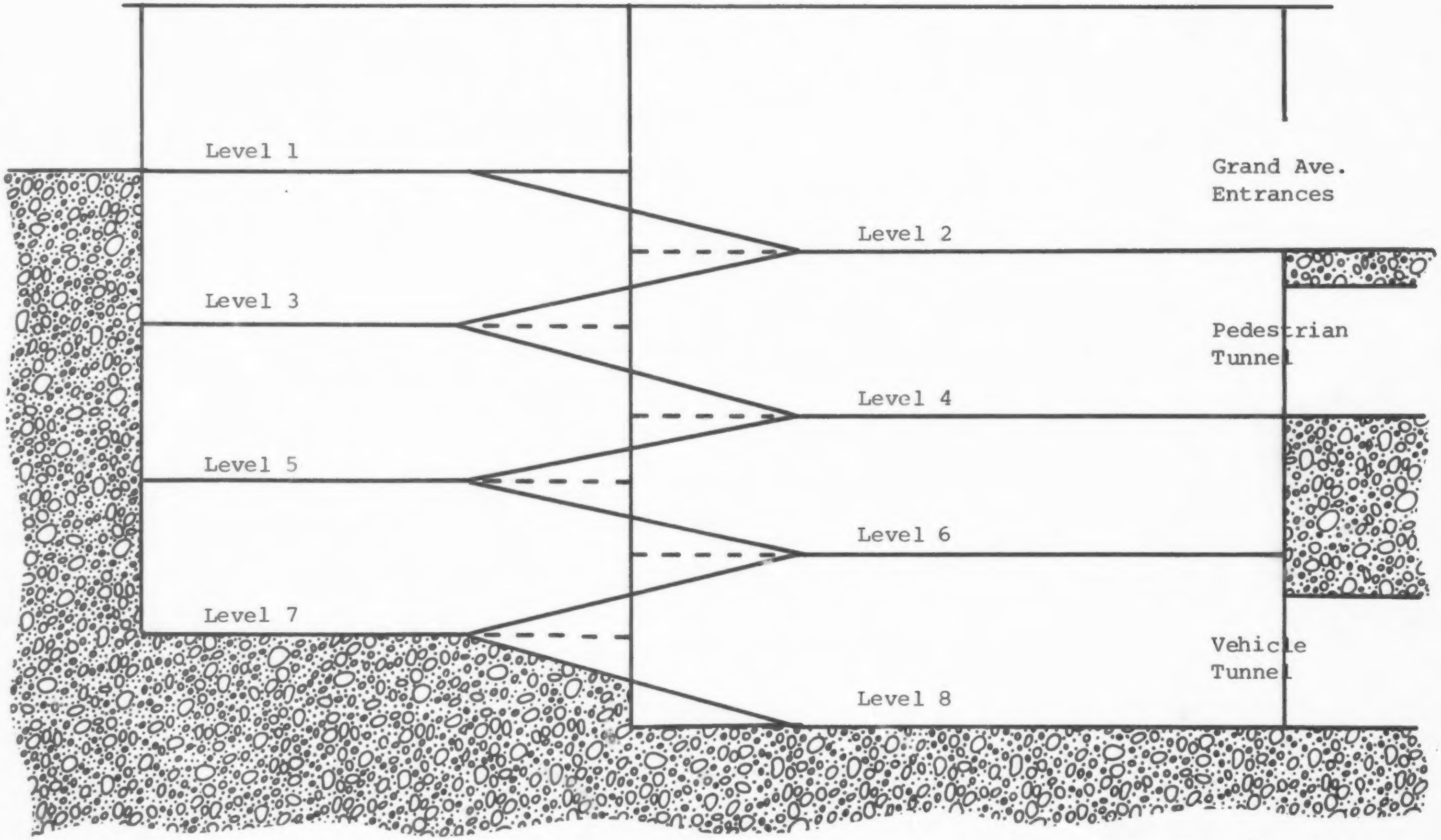
The typical and severe parking garage exposure situations were chosen in Section IV on the basis of size and ventilation capacity. The enclosed space model explained in Section III B 2 was used to determine the pollutant concentrations within the two parking garages.

Recall that the enclosed space model contains an effective ventilation factor. The numerical value of this factor is not well defined in the literature. However, an unpublished CO measurement study done by Los Angeles county in the severe case parking garage(86) was utilized in this project to determine the effective ventilation factor. For that reason, the severe exposure case will be presented first.

1. Severe Parking Garage Concentrations

The Music Center parking garage in downtown Los Angeles was chosen as the severe exposure situation. This is an 8 level underground parking garage. A sketch of the garage cross section is shown in Figure 23. A floor plan of a typical level (level 5) is shown in Figure 24. The most severe exposure occurs at the end of an evening event, when all cars are trying to exit at the same time.

The situation modeled used the original ventilation system which existed prior to 1979. In that system, the mechanical ventilation was on the exhaust side only. Fresh air entered from the street level entrances (level 2), the pedestrian tunnel on level 4, and the vehicle tunnel on level 8. Following many complaints about the garage ventilation, a complete redesign of the ventilation system was begun in 1977. The current system uses blowers to supply the air through ducts, exhausting through the extrances. The current ventilation capacity is almost three times the original capacity. For the purposes of this project, however, the original ventilation system best fits the severe exposure condition.


Level 1
Level 2
Level 3
Level 4
Level 5
Level 6
Level 7
Level 8
Grand Ave. Entrances
Pedestrian Tunnel
Vehicle Tunnel

NOTE: Not to Scale

Figure 23. Sketch of parking level arrangement, Music Center Garage

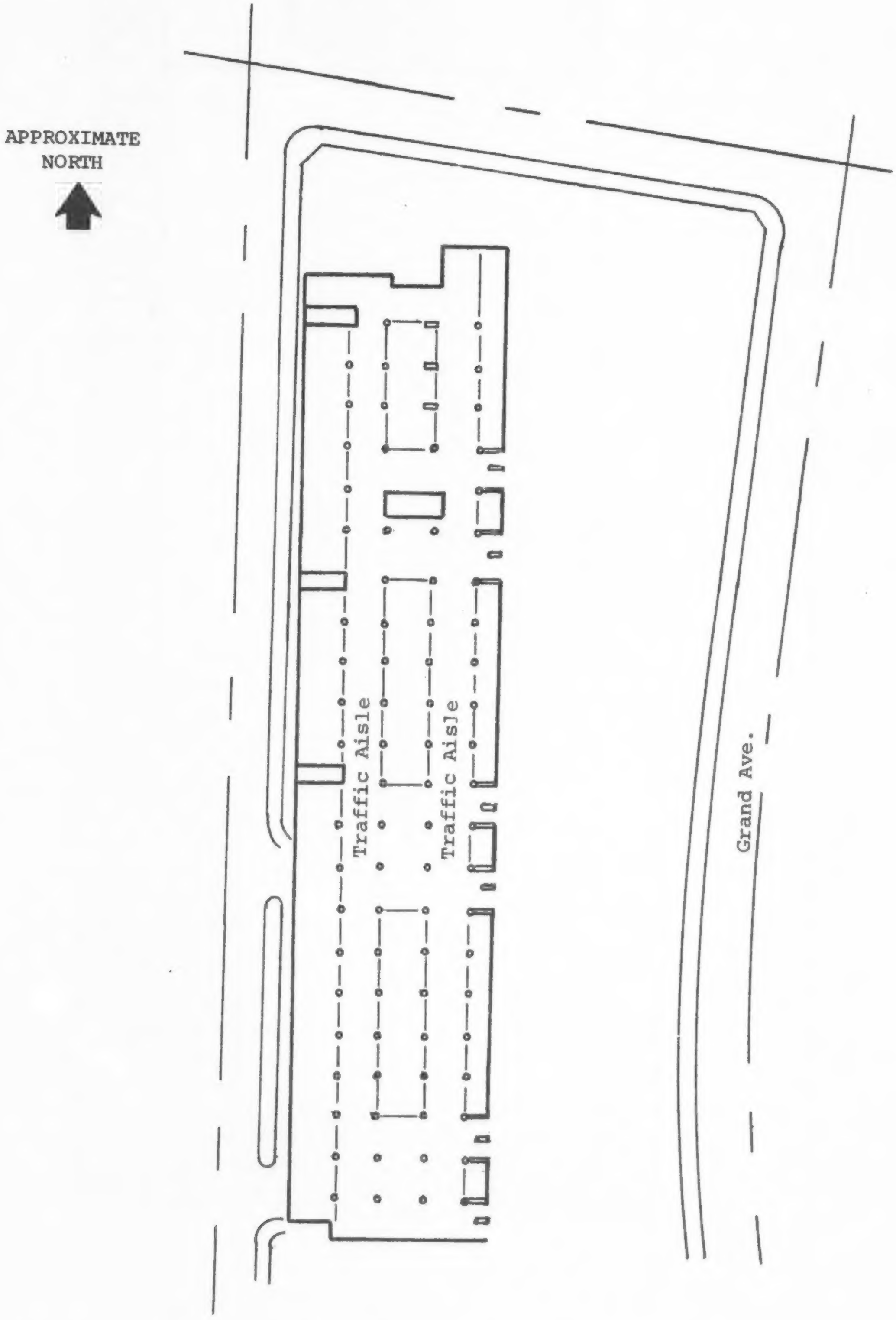

APPROXIMATE NORTH
Traffic Aisle
Traffic Aisle
Grand Ave.

Figure 24. Floor plan of parking level 5 of Music Center Garage

The air supply reaches the individual parking levels through the ramps, so the pollutant concentrations in the ramps must be also calculated to obtain the pollutant concentration of the air entering the parking level. The air flow in each between-level ramps will be different, since some air coming down the ramps is exhausted at each level. The vehicle capacity, ventilation, and volume of each level and interlevel ramp is shown in Table 16.

TABLE 16. DATA FOR MUSIC CENTER GARAGE

Levels	Parking Spaces	Volume cubic feet	Ventilation cfm
1	120	636,262	39,820
2	190	1,000,407	35,430
3	195	701,760	28,770
4	181	705,546	40,610
5	226	737,316	38,100
6	216	795,328	48,600
7	223	737,316	35,400
8	231	795,328	44,200
Total	1,582	6,109,263	310,930
Ramps			
Street to 3	-	18,445	52,500
3 to 4	-	3,400	47,705
4 to 5	-	3,400	40,937

From an analysis of the CO study performed on the garage in 1978, it appeared to take between 20 and 30 minutes to clear the garage after a performance. Following other studies of parking garages, it is assumed that approximately 25 percent of the vehicles are in operation at any instant during this time.(62)

The remaining variable requiring definition is the effective ventilation factor for each equation. Since the effective ventilation factor is a function of how the pollutant is introduced into the garage as well as the ventilation scheme, there is a different ventilation factor for each of the three equations. From an analysis of the CO measurements done in 1978, it appeared that a reasonable value of the ventilation factor for the vehicle generated pollutant is 0.3. For the initial concentration and background contributions, the ventilation factor is 1.0.

For the severe situation, the receptor will be assumed to be located on level 5 and go up to exit the garage onto Grand Ave. at level 2 after a performance at the Music Center. It is assumed that the receptor spends 8 minutes on level 5, and 4 minutes in the ramp area. For purposes of this severe case, it is assumed that the receptor is one of the last vehicles out of the garage and so experiences the maximum concentration. This maximum occurs at approximately 20 minutes after the garage starts to empty.

The ramps will approach an equilibrium concentration in less than three minutes. This means that the initial concentration will have decayed to essentially zero, the inlet air contribution will be the inlet air concentration and the vehicle contribution will be the exhaust emission rate divided by the ventilation rate. As the air flows downward through the ramps, the concentration in each ramp level becomes the inlet air concentration for the next ramp.

To calculate the ramp concentration, it was assumed there were three active vehicles on each ramp at all times, except for the ramp from level 3 to the street which contained 15 cars. For an assumed emission rate of 1 g/min, an initial concentration of 1 $\mu g/m^3$, and a street air concentration of 1 $\mu g/m^3$, the concentrations after 20 minutes in the ramps are:

		Ramp Street to 3	Ramp 3 to 4	Ramp 4 to 5
C_1	=	0	0	0
C_2	=	1 $\mu g/m^3$	1 $\mu g/m^3$	1 $\mu g/m^3$
C_3	=	$\frac{15(1 \times 10^6)}{(1)(52,500)(0.02832)}$	$\frac{3(1 \times 10^6)}{(1)(47705)(0.02832)}$	$\frac{3(1 \times 10^6)}{(1)(40937)(0.02832)}$
C_3	=	10,100 $\mu g/m^3$	2,200 $\mu g/m^3$	2,600 $\mu g/m^3$
C_{total}	=	10,101 $\mu g/m^3$	12,300 $\mu g/m^3$	14,900 $\mu g/m^3$

Thus, the pollutant concentration in the air entering level 5 is the sum of the three C_3 terms (ignoring the 1 $\mu g/m^3$ street concentration).

While the ramps reach equilibrium quickly, the parking levels do not. The concentration in level 5 after 20 minutes, assuming a 1 $\mu g/m^3$ initial concentration, 14,900 $\mu g/m^3$ inlet air concentration, 1 g/minute emission rate and 56 active cars is:

$$C_1 = (1)(\exp(-(1)(38100)(20)/737316)$$

$$C_1 = 0.36\ \mu g/m^3$$

$$C_2 = 14{,}900\ (1 - \exp(-(1)(38100)(20)/737316)$$

$$C_2 = 9{,}600\ \mu g/m^3$$

$$C_3 = \frac{(56)(1\mathrm{x}10^6)}{(0.3)(38100)(0.02832)}\ (1 - \exp(-(1)(38100)(20)/737316)$$

$$C_3 = 46{,}100\ \mu g/m^3$$

Table 17 lists the concentrations in the various areas of the garage together with the values of the parameters required to calculate those concentrations.

2. Typical Parking Garage Concentrations

The Convention Center Parking Garage in San Antonio, Texas, was chosen for the typical exposure situation. This parking garage is an above ground, open structure with natural ventilation only. It is 5 levels high and can store up to 461 vehicles. Its primary use is during special events held at the nearby Convention Center complex. This type of useage is referred to as surge type parking and resembles useage common to large office building areas. A sketch of the garage is shown in Figure 25. A floor plan of a typical level is shown in Figure 26.

The various parking level surfaces are vertically spaced 10 feet apart, and are staggered with intermediate levels, giving the appearance of split level construction. For application of the model, a given parking level will be considered as being isolated from the other parking levels, and will then be considered as an independent enclosed space. The various levels are connected by ramps with about a 9 percent grade. These ramps will be considered separately, due to the higher incidence of traffic queuing in the relatively confined area. The drive from entrance to uppermost level is approximately 1640 feet via primary driveway, of which nearly a fourth is ramped.

The floor area of a parking level is approximately 39,500 ft^2. Ceiling clearance is 7 1/2 ft. Since the ceiling is made of exposed structural shapes, for volume considerations the height is taken to be 9 ft. These dimensions give a volume of about 356,000 ft^3 per enclosed parking level. As indicated in the illustrations, the parking levels are served by two ramp sections. Each section is approximately 45 ft in height, 25 ft wide and 52 ft long, which represents a volume of 58,500 ft^3 for each "ramp room."

TABLE 17. AMBIENT CONCENTRATIONS FOR RECEPTOR IN A PARKING GARAGE SEVERE CASE-LOS ANGELES MUSIC CENTER GARAGE (Pre 1979)

	Level 5	Ramp 5 to 4	Ramp 4 to 3	Ramp 3 to Street
Number of active cars	56	3	3	15
Volume, cubic feet	737,316	3,400	3,400	18,445
Ventilation rate, cfm	38,100	40,937	47,705	52,500
Emission factor, g/min	1	1	1	1
Intake air concentration, $\mu g/m^3$	14,900	12,300	10,100	1
Initial ambient concentration, $\mu g/m^3$	1	1	1	1
Ventilation factor, exhaust emission	0.3	1.0	1.0	1.0
Ventilation factor, intake air	1.0	1.0	1.0	1.0
Ventilation factor, initial conc.	1.0	1.0	1.0	1.0
After 20 minutes:	55,700	14,900	12,300	
C_1, contribution of initial conc., $\mu g/m^3$	0.36	0	0	0
C_2, contribution of intake conc., $\mu g/m^3$	9,600	12,300	10,100	0
C_3, contribution of exhaust emissions, $\mu g/m^3$	46,100	2,600	2,200	10,100

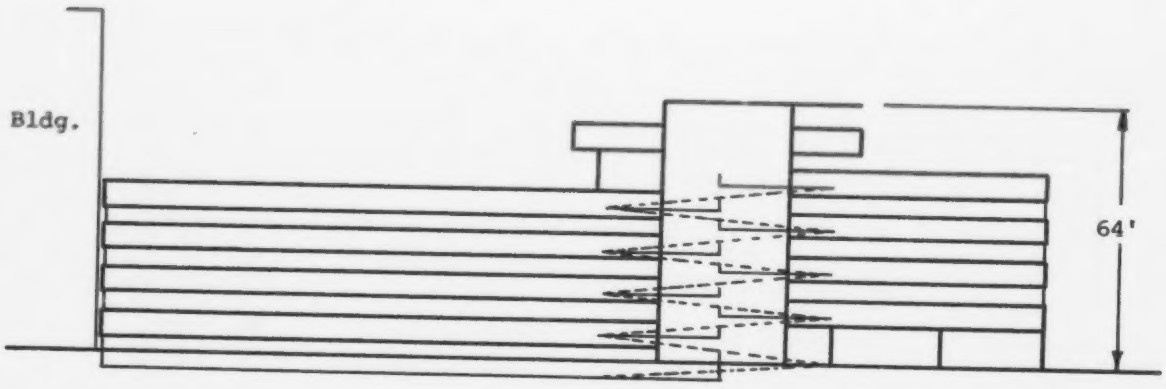


Figure 25. Parking level arrangement, San Antonio Convention Center Parking Garage

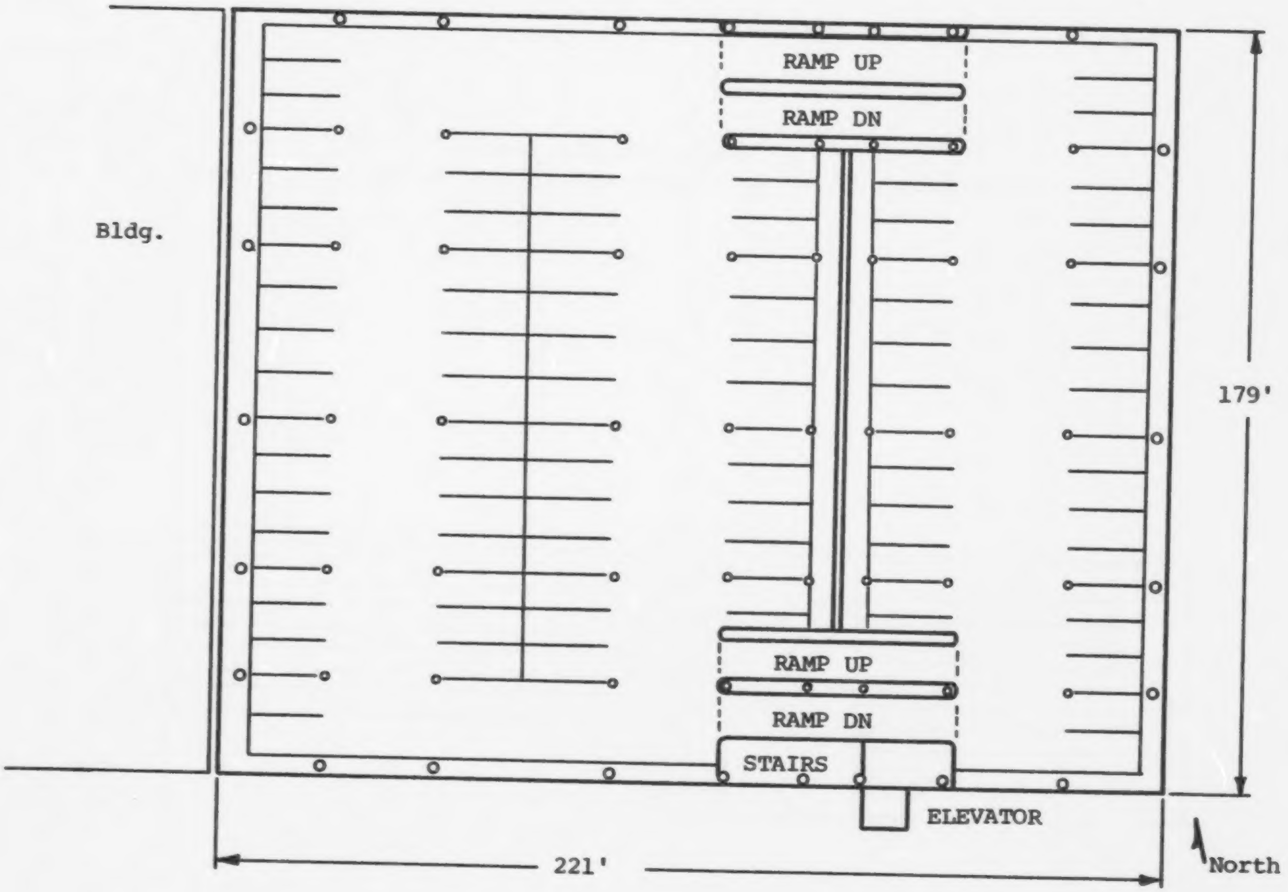

Bldg.
RAMP UP
RAMP DN
RAMP UP
RAMP DN
STAIRS
ELEVATOR
179'
221'
North

Figure 26. Typical parking level floor plan for Convention Center Garage

This open parking garage relies solely on natural ventilation, and is dependent on the ambient conditions. The overall "enclosed" portion of the garage structure can be considered as a large room with one large window in each wall. The percentage of open space was calculated using the total open area divided by the area of the corresponding wall (external dimensions). The east wall projection is about 7000 ft^2, with an open area of 40 percent corresponding to a 2400 ft^2 opening. The west wall is completely blocked by an adjacent building. Both north and south walls project areas of 8800 ft^2 each, with an open area of about 24 percent corresponding to 2100 ft^2 opening. In an effort to estimate the air flow, a 7 mph wind speed is assumed. This speed is a typical for the country as a whole (see Figure 14 in Section IV). It is assumed that the wind is from the southeast, so that the wind is skewed to the south and east walls of the structure. In San Antonio, the wind is from the southeast, between 3 and 7 mph approximately three percent of the time. The effectiveness of the open areas is assumed to be about 0.4, resulting in approximately 714,000 cfm through the east opening and 518,000 cfm through the south opening. This situation results in a total ventilation of the enclosed portion of the structure of about 1,232,000 cfm. Dividing by the four enclosed levels yields 308,000 cfm ventilation per level.

The ramp area or "ramp room" is an integral part of the structure. Natural ventilation is provided through access openings from individual levels. Ventilation of the ramp room is aided by the chimney effect due to warm engine air rising. It is assumed that the ramp room would have a ventilation rate of 61,600 cfm.

This garage has more diffuse sources of ventilation than the Music Center garage used in the severe case. The effective ventilation factor should therefore be somewhat closer to one than the severe case. A ventilation factor of 0.4 was assumed for the vehicle exhaust equation. The effective ventilation coefficients for the initial concentration and inlet air equations were again assumed to be 1.0.

For this typical situation, the receptor will be assumed to be located on level 4 and exit down to the street level, level 1, following an event at the Convention Center. It is assumed that the receptor spends 4 minutes on level 4 and 4 minutes in the "ramp room". For purposes of this exposure case, it is assumed that the receptor starts to exit the garage approximately 15 minutes after it has started to empty. Level 4 has a capacity of 92 cars. It is assumed that it is 75 percent full and that 25 percent of the cars are active at all times during the emptying process. Thus, there are 17 cars active at all times on level 4. It is also assumed that there are 12 active vehicles in the ramp room at all times. Assuming an initial concentration of 1 $\mu g/m^3$, an inlet air concentration of 1 $\mu g/m^3$, and an exhaust concentration of 1 g/min (1×10^6 μg/min) the concentrations on level 4 at $t = 15$ minutes are:

$$C_1 = 1.0 \times (\exp - (1.0 \times 308{,}000 \times 15/356{,}000))$$

$$C_1 = 0.0\ \mu g/m^3$$

$$C_2 = 1.0 \times (1 - \exp - (1.0 \times 308{,}000 \times 15/356{,}000))$$

$$C_2 = 1.0\ \mu g/m^3$$

$$C_3 = \frac{17 \times (1\times 10^6)}{0.5 \times 308{,}000 \times 0.02832} (1 - \exp (0.5 \times 308{,}000 \times 15/356{,}000))$$

$$C_3 = 3{,}900\ \mu g/m^3$$

For the ramp room the concentrations are:

$$C_1 = 1.0 \times (\exp - (1.0 \times 61{,}600 \times 15/58{,}500))$$

$$C_1 = 0.0\ \mu g/m^3$$

$$C_2 = 1.0 \times (1 - \exp - (1.0 \times 61{,}600 \times 15/58{,}500))$$

$$C_2 = 1.0\ \mu g/m^3$$

$$C_3 = \frac{12 \times (1\times 10^6)}{0.5 \times 61{,}600 \times 0.02832} (1 - \exp - (0.5 \times 61{,}600 \times 15/58{,}500))$$

$$C_3 = 13{,}750\ \mu g/m^3$$

Table 18 lists the parameters required by the model equations together with the concentrations after 15 minutes for the typical exposure case.

3. Use of Parking Garage Concentrations With Other Emission Factors

To demonstrate how these concentrations can be used with other pollutants, the CO level in each of the two garages will be calculated.

Severe Case (Music Center garage). A reasonable CO emission rate for California in 1978 is 7.25 g/min for cars on a parking level and 10 g/min for cars on the ramp.(98) Assume also that initial concentration and outside background are negligible. The following CO levels are obtained:

$$\begin{array}{llrl}
\text{Level 5:} & C_2 = & 9{,}600 \times 10 \quad = & 96{,}000\ \ g/m^3 \\
 & C_3 = & 46{,}100 \times 7.25 = & \underline{334{,}225\ \ g/m^3} \\
 & C_{Total} = & & 430{,}255\ \ g/m^3 \text{ or } 374 \text{ ppm CO}
\end{array}$$

Ramp 5 to 4: 14,900 × 10 = 149,000 $\mu g/m^3$ or 129 ppm CO

Ramp 4 to 3: 12,300 × 10 = 123,000 $\mu g/m^3$ or 107 ppm CO

Ramp 3 to street: 10,000 × 10 = 101,000 $\mu g/m^3$ or 88 ppm CO

The level 5 CO concentration can be compared with the CO concentrations measured on level 5 on March 21, 1978, when the garage was approximately three quarters full.(86) On that date, 20 minutes after a performance ended at the Music Center, a level 5 CO reading reached a maximum of 325 ppm. The calculated value at 20 minutes of 374 ppm, is in good agreement, considering that it was obtained assuming a full garage.

TABLE 18. AMBIENT CONCENTRATIONS FOR RECEPTOR IN A PARKING GARAGE TYPICAL CASE-SAN ANTONIO CONVENTION CENTER GARAGE

	Parking Level	Ramp Room
Number of active cars	17	12
Volume cubic feet	356,000	58,500
Ventilation rate, cfm	308,000	61,600
Emission factor, g/min	1.0	1.0
Intake air concentration, $\mu g/m^3$	1	1
Ventilation factor, exhaust emissions	0.5	0.5
Ventilation factor, intake air	1	1
Ventilation factor, initial conc.	1.0	1.0
After 15 minutes:	1.0	1.0
C_1, contribution of initial conc., $\mu g/m^3$	0	0
C_2, contribution of intake conc., $\mu g/m^3$	1	1
C_3, contribution of exhaust emissions, $\mu g/m^3$	3,900	13,750

While the severe case was taken as a mechanically ventilated garage, it should be pointed out that concentrations of the same order of magnitude are possible with open construction, naturally ventilated garages when the wind speed is below two miles per hour.

Typical Case (Convention Center Garage). A CO emission rate for 1978 on the parking level of 10 g/min and a CO emission rate of 13 g/min on the ramps were assumed. The CO concentration in the intake air is 3 ppm, or 3448 $\mu g/m^3$. The parking garage CO concentrations are:

Parking level: $C_2 = 1 \times 3448 = 3,448\ \mu g/m^3$
$C_3 = 3,900 \times 10 = \underline{39,000\ \mu g/m^3}$
$42,448\ \mu g/m^3$ or 37 ppm CO

Ramp Room: $C_2 = 1 \times 3448 = 3,448\ \mu g/m^3$
$C_3 = 13,750 \times 13 = \underline{178,750\ \mu g/m^3}$
$182,198\ \mu g/m^3$ or 159 ppm CO

C. Roadway Tunnel Concentration

The calculations for ambient pollutant concentrations in the typical and severe tunnel exposure situations also make use of the enclosed space model. The tunnel exposure is assumed to take place after the tunnel concentrations have essentially reached equilibrium.

1. Typical Roadway Tunnel Concentrations

As mentioned in Section IV, the Lowery Hill tunnel on I-94 on the west side of Minneapolis was chosen for the typical tunnel exposure situation. Tunnel traffic and ventilation data were obtained from the District 5 Office of the Minnesota Department of Transportation.(87) This 1500 foot long tunnel consists of two tubes of rectangular cross section, each with three lanes of one way traffic.

The average daily traffic count is approximately 60,250 vehicles. The morning rush hour traffic used for this situation is assumed to be nine percent of the ADT. The average speed in the east bound tube during the morning rush hour is 45 miles per hour. At this rate it takes 23 seconds to traverse the tunnel. From Figure 10, at this speed there are an average of 25 vehicles in the east bound tube at all times during the morning rush hour.

The tunnel uses a semi-transverse ventilation scheme. The maximum ventilation rate is 536,000 cfm per tube. To this rate is added 10 percent of the total capacity to account for the piston effect of the cars.

Since this situation takes place at the end of the morning rush hour, the pollutant concentration has essentially reached equilibrium. This means that the initial concentration has decayed to zero, the ventilation contribution is equal to the background concentration, and the vehicle contribution is equal to the total vehicular emission rate divided by the effective ventilation.

Since roadway tunnels have high levels of ventilation and the air is thoroughly mixed by the vehicle wakes, the effective ventilation factor (see Section III) for the vehicle pollutants is assumed to be 1.0.

For an assumed emission factor of 1 g/mile (1×10^6 μg/mile) the pollutant concentration in the tunnel is then:

$$C_3 = \frac{25(1 \times 10^6)(45)}{60(1)(536{,}000 \times 1.10)(0.02832)}$$

$$C_3 = 1{,}123\ \mu g/m^3$$

A summary of the typical exposure situation parameters is contained in Table 19 following the presentation of the severe tunnel exposure case.

2. Severe Roadway Tunnel Concentrations

The Baltimore Harbor Tunnel was chosen for the severe case. This 6700 foot long tunnel is part of the Baltimore Harbor Throughway. It has two tubes, each with two lanes of one way traffic.

The latest ADT counts were obtained from the International Bridge, Tunnel and Turnpike Association.(88) The traffic averages about 60,000 vehicles per day or approximately 3000 vehicles per hour per tube during rush hour. The rush hour traffic speed through the tunnel averages 25 mph. From Figure 10 (Section IV), it can be calculated that there are an average of 165 vehicles in a tube at all times during the rush hour.

The tunnel has a fully transverse ventilation system. The total maximum ventilation rate is 800,000 cfm per tube. To this rate is added 50,000 cfm for the piston effect of the cars entering the tube.(89)

For this tunnel also, the effective ventilation factor for the vehicle emissions will be assumed to be 1.0. Since the exposure situation occurs at the end of the rush hour, the pollutant concentrations have essentially reached equilibrium and are equal to the total vehicle emission rate divided by the effective ventilation rate. Using 1 g/mile per vehicle (1×10^6 μg/mile), the ambient concentration in the tunnel is:

$$C_3 = \frac{(1\times10^6)(165)(25)}{(1)(850{,}000)(0.02832)(60)} = 2856\ \mu g/m^3$$

Table 19 summarizes the physical variables and the ambient concentration for the severe tunnel exposure situation.

3. Use of Tunnel Concentrations with Other Emission Factors

To use the ambient concentrations shown in Table 19 to obtain the ambient concentrations other pollutants, multiply the ambient concentrations by the individual vehicle emission rate in grams per mile. For example, to obtain the 1969 CO concentration in the typical exposure case (for comparison with the severe case) multiply the ambient concentration by the assumed 1969 CO emission factor at 45 mph of 45 g/mile.

TABLE 19. AMBIENT CONCENTRATIONS FOR RECEPTOR IN ROADWAY TUNNEL - TYPICAL AND SEVERE CASES

	Typical Case	Severe Case
Tunnel location	Lowery Hill Minneapolis, MN	Baltimore Harbor Baltimore, MD
Ventilation rate, one tube, cfm[a]	589,600	850,000
Number of vehicles in one tube	25	165
Intake air concentration, g/m^3	1	1
Emission factor, g/mile	1.0	1.0
vehicle speed, mph	45	25
Ventilation factor, intake air	1.0	1.0
Ventilation factor, exhaust emissions	1.0	1.0
Concentration:		
C_2, contribution of intake air µg/m^3	1	1
C_3, contribution of exhaust emission, µg/m^3	1123	2856

---

[a] including ventilation air from vehicle piston effect

$$C_3 = 1123 \times 45 = 50{,}535\ \mu g/m^3 \text{ or } 44 \text{ ppm CO}$$

While no measurements are available for comparison, this CO concentration does not appear unreasonable.

The Baltimore Harbor Tunnel has been the subject of considerably more study. Reference 89 reports on a CO measurement and modeling study done in 1969 and 1970. To compute the CO concentration in the severe case for 1969, the ambient concentration shown in Table 19 is multiplied by the 25 mph CO emission factor for that era. From CO emissions given in Reference 89, a CO value of 65 g/mile would appear to be appropriate. The tunnel concentration is then:

$$C_3 = 2856 \times 65 = 185{,}640\ \mu g/m^3 \text{ or } 163 \text{ ppm CO}$$

This value of 163 ppm can be compared with the statement in Reference 89, that the CO level in the Baltimore Harbor Tunnel "rarely exceeded 180 ppm during peak traffic periods."

D. Street Canyon Concentrations

Two street canyons were chosen in Section IV to represent typical and severe exposure situations. "Typical" and "severe" refer more to street width than any other parameter. This is because the dispersion model chosen is limited to a height to width ratio of 2.0. As explained in Section IV, what constitutes severe traffic depends on the emission type being considered. For some emissions, a severe case is low speed, high density; for others a higher speed, lower density. Therefore, street width became the controlling parameter. A four lane street was chosen as the typical exposure situation, and a six lane street as the severe exposure situation. Each situation will be modeled with two different traffic densities, using the model selected in Section III.

1. Typical Street Canyon Concentrations

For the typical exposure situation, a street canyon in San Antonio, Texas, was used. The street is Houston Street (one way) between the cross streets of Navarro and St. Marys. (See Figure 27). The pertinent physical data for this street canyon are:

- Block length - 128 meters
- "Canyon" width including sidewalks = 18.6 m
- Average building height = 33.7 m
- Height to width ratio: 1.81
- Street orientation - West to East (270 - 090°)
- Distance from street center to sidewalk center = 8.8 m

The street canyon dispersion model chosen is valid for wind directions within ±45 degrees of perpendicular to the street. Houston Street runs West to East, therefore wind directions from SE to SW would fall within these limits. The wind direction in San Antonio is between SE and SW 47 percent of the time.

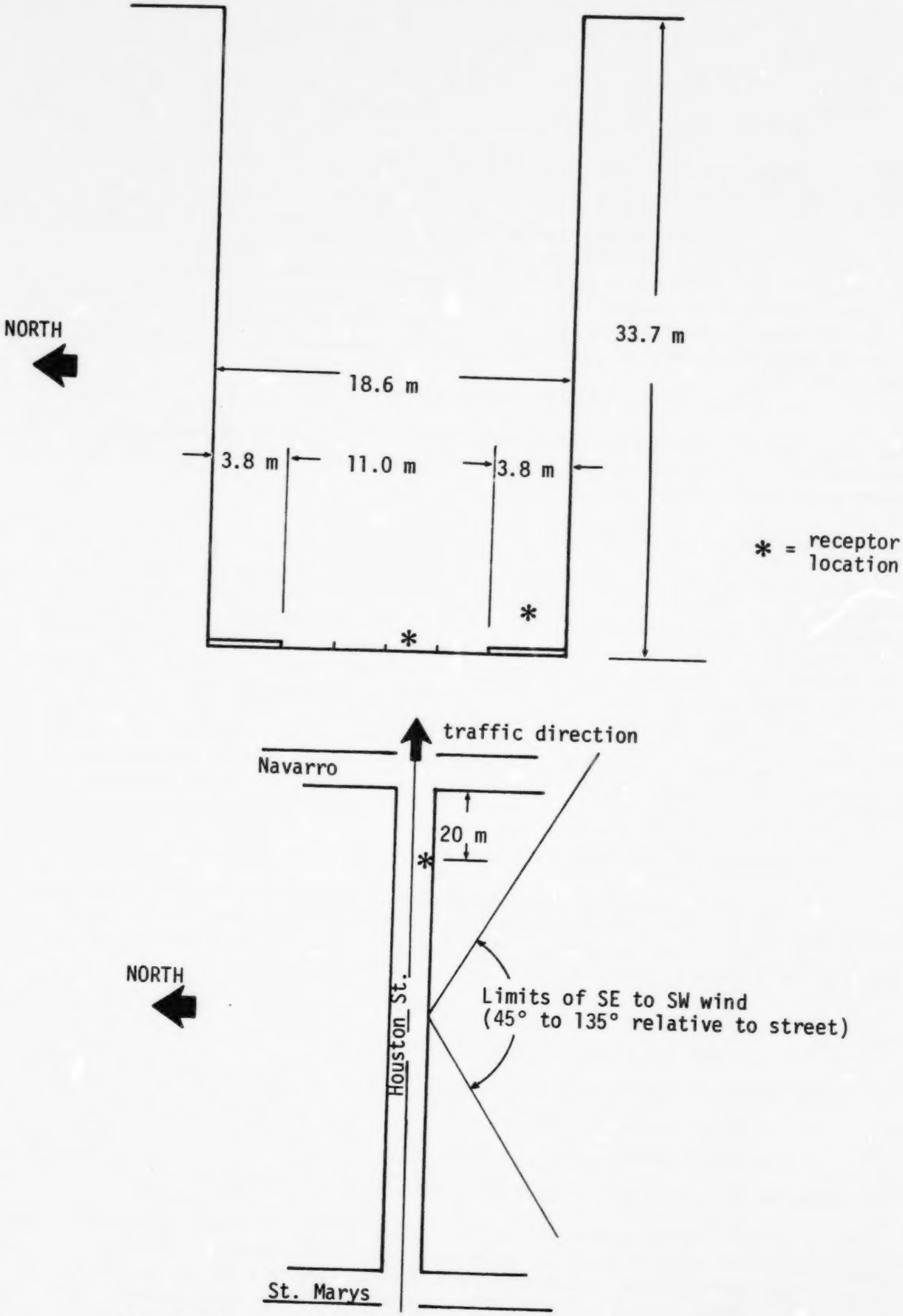

NORTH
33.7 m
18.6 m
3.8 m
11.0 m
3.8 m
* = receptor location
traffic direction
Navarro
20 m
NORTH
Houston St.
Limits of SE to SW wind
(45° to 135° relative to street)
St. Marys

Figure 27. Houston Street between Navarro and St. Marys, San Antonio, Texas

On a national basis, a typical (median) wind speed would be approximately 7 knots (8 mi/hr, 3.6 m/sec). In San Antonio, when the wind is from SE to SW, the wind speed is 8 to 12 miles/hr (3.6 m/sec to 5.4 m/sec) approximately 38 percent of the time. Thus, the wind is from SE to SW at 8 to 12 miles/hr approximately 18 percent of the year.

To account for both the low speed, high traffic density case and the higher speed, lower density case, two assumed traffic flow and speed combinations were used. For the four lanes of Houston Street, these combinations were 800 vehicles per hour (0.222 vehicles/sec) at 5 mph and 1600 vehicles per hour (0.444 vehicles/sec) at 20 mph. For comparison, the actual rush hour traffic flow is approximately 1300 vehicles per hour.

Two receptor locations were chosen, The first was a point at the midpoint of the sidewalk, 1.5 meters above the ground. The second receptor location was in a vehicle in the street with a slant distance from the assumed pollution line source of one meter. From data taken during the development of the model, it appeared that the background concentration from other vehicles in the area could be assumed to be equal to the street canyon contribution at a height of three meters above the sidewalk.(25,26) Since the background is caused by other vehicles in the area, and since it is an appreciable fraction of the total concentration, it will be included in the calculation of the ambient concentration.

As with all the microscale situations modeled in this study, the vehicle emission factor was selected to have a unity value. In this case, one g/mile.

Using an emission factor of 1 g/mile per vehicle at 800 vehicles per hour, the pollutant generation rate is:

$$Q_L = \left(\frac{1\text{ g}}{\text{vehicle mile}}\right) \times \left(\frac{1\text{ mile}}{1609\text{ meters}}\right) \times \left(\frac{0.222\text{ vehicles}}{\text{sec}}\right)$$

$$Q_L = 1.38 \times 10^{-4}\text{ g/sec m}$$

Using the data set forth above with the street canyon model from Section III yields the following street contribution to the ambient concentration for a person on the upwind sidewalk.

$$C_V = \frac{7 \times 10^6\ 1.38 \quad \times 10^{-4}}{(3.6 + 0.5)(8.93 + 2)} = \frac{7 \times 1.38 \times 10^2}{4.1 \times 10.93}$$

$$C_V = 21.56\ \mu g/m^3$$

The background concentration is assumed equal to the vehicle contribution at 3 meters above the sidewalk. In this case, the slant distance is 9.3 meters, with a resulting concentration of 20.85 $\mu g/m^3$. The total concentration experienced by a person on the sidewalk with a traffic flow of 800 vehicles per hour is then:

$$C_T = C_v + C_b = 21.6 + 20.8 = 42.4\ \mu g/m^3$$

A person in a vehicle in the street canyon will experience a higher concentration since the applicable slant distance is smaller. For a person in a vehicle, the slant distance is assumed to be one meter. The concentrations at this point are:

$$C_v = 78.54\ \mu g/m^3$$

$$C_T = C_v + C_b = 78.5 + 20.8 = 99.3\ \mu g/m^3$$

For 1600 vehicles per hour (0.444 vehicles/sec), the pollutant generation rate for a 1 g/mile emission factor is:

$$Q_L = 2.76 \times 10^{-4}\ g/sec\ m$$

For the sidewalk receptor the concentrations are:

$$C_V = \frac{(7\ 10^6) \times (2.76\ 10^{-4})}{(3.6+0.5) \times (8.93+2)}$$

$$C_V = 43.11\ \mu g/m^3$$

$$C_b = \frac{(7\ 10^6) \times (2.76\ 10^{-4})}{(3.6+0.5) \times (9.3+2)}$$

$$C_b = 41.70\ \mu g/m^3$$

$$C_T = C_V + C_b = 43.11 + 41.70 = 84.8\ \mu g/m^3$$

For the receptor in a vehicle (slant distance of one meter) with a traffic flow of 1600 vehicles per hour is:

$$C_V = 157.07\ \mu g/m^3$$

$$C_t = 157.1 + 47.1 = 198.8\ \mu g/m^3$$

The street canyon physical parameters and the ambient concentrations for both traffic flows are summarized in Table 20, following the presentation of the severe exposure situation.

2. Severe Street Canyon Concentrations

Since the model limited the canyon height to width ratio to 2.0, the severe case was chosen on the basis of number of traffic lanes, plus the more practical consideration of availability of the necessary information. A local aerial mapping company has stereographic aerial photographs of the Houston area from which building heights could be determined. Since downtown Houston streets are in general six-lane one-way streets with heavy traffic, a street canyon in Houston appeared to be a good location for the severe exposure case. However, care had to be taken to insure that a street canyon with less than 2.0 height-to-width ratio was chosen. The final selection was Main Street (one-way) between the cross streets of Capitol and Rusk. A sketch of the block showing building heights and wind orientation is presented as Figure 28. An aerial photograph of this block is shown in Figure 29. The pertinent physical data for this street canyon are:

- Block length = 86 m
- "Canyon" width including sidewalks = 27 m
- Average building height (leeward side) = 38 m
- Height to width ratio = 1.39
- Street orientation - NE to SW (045 to 225°)
- Distance from street center to sidewalk center = 11.4 m

The assumed wind direction will be southeasterly. Since wind direction 45 degrees on either side of perpendicular to the street is considered to be perpendicular by the model, the wind direction can be between East and South. At the Houston Intercontinental Airport at 6 a.m. and 9 a.m., the wind is from these directions 32 and 44 percent of the time, respectively.

For a severe exposure situation, the wind speed should be as low as possible. There are two considerations. The first is that for a given street canyon, there is a minimum wind speed that will produce a helical wind flow pattern in the street which is required for use of the model. The second consideration is that it should be a wind speed which actually occurs at the chosen location. Using the equation for wind penetration, it can be ascertained from Figure 16 in Section IV that for a street 27 meters wide and a building height of 38 meters, the minimum wind speed to have a helical flow pattern is approximately 0.9 meters/sec (2.1 miles per hour). From wind distribution at the Houston Intercontinental Airport, at 6 a.m. and 9 a.m. the wind is between East and South at 0 to 3 miles per hour (0 to 6.7 m/sec) 6.9 and 4.3 percent of the time, respectively. Assuming the wind speed is evenly distributed in the interval, the severe wind condition of 0.9 meters per second, perpendicular to the street does indeed occur at the location chosen for the severe exposure situation.

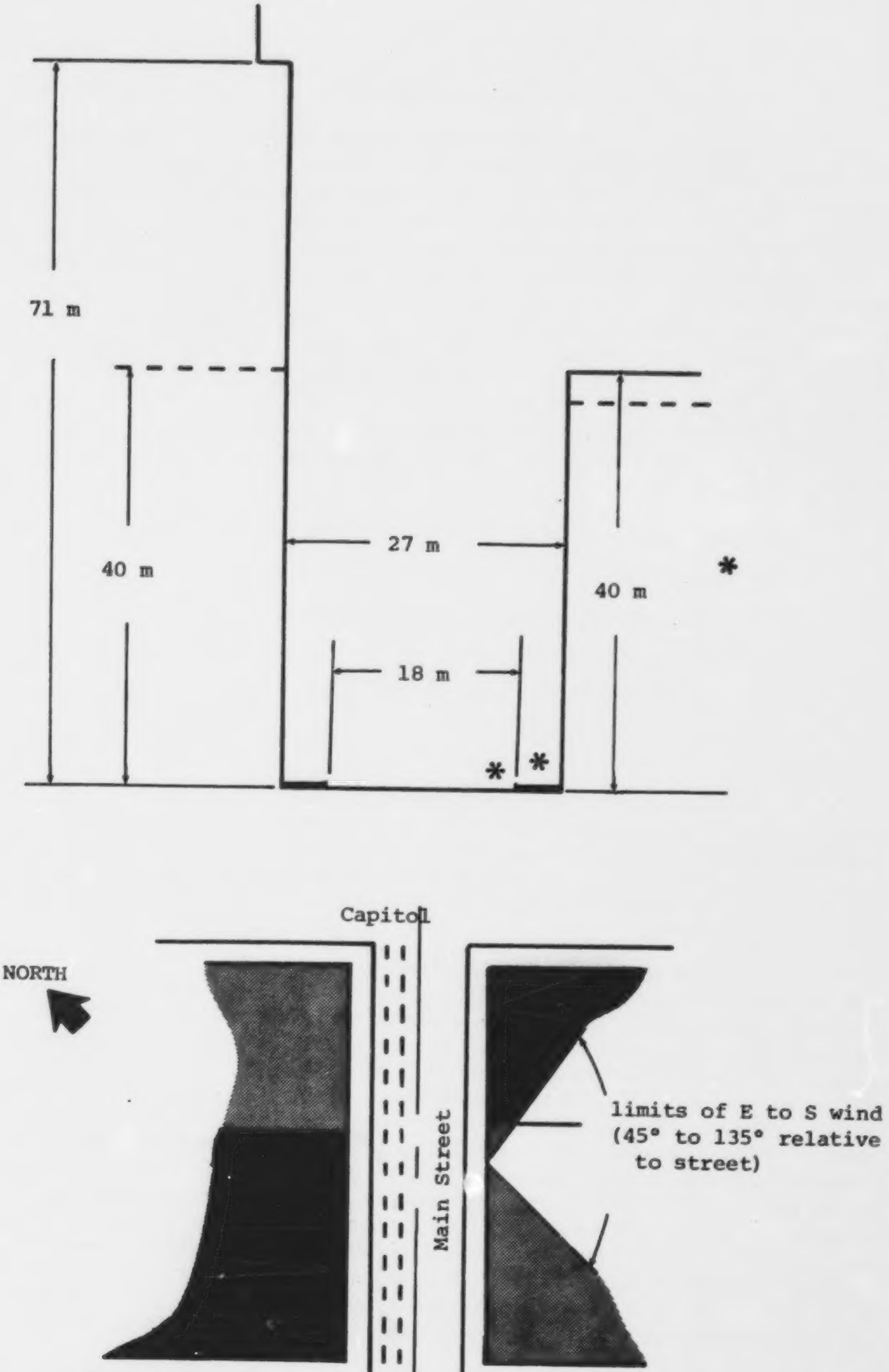

71 m
40 m
27 m
18 m
40 m
Capitol
NORTH
Main Street
limits of E to S wind
(45° to 135° relative
to street)
Rusk

Figure 28. Main Street between Capitol and Rusk, Houston, Texas

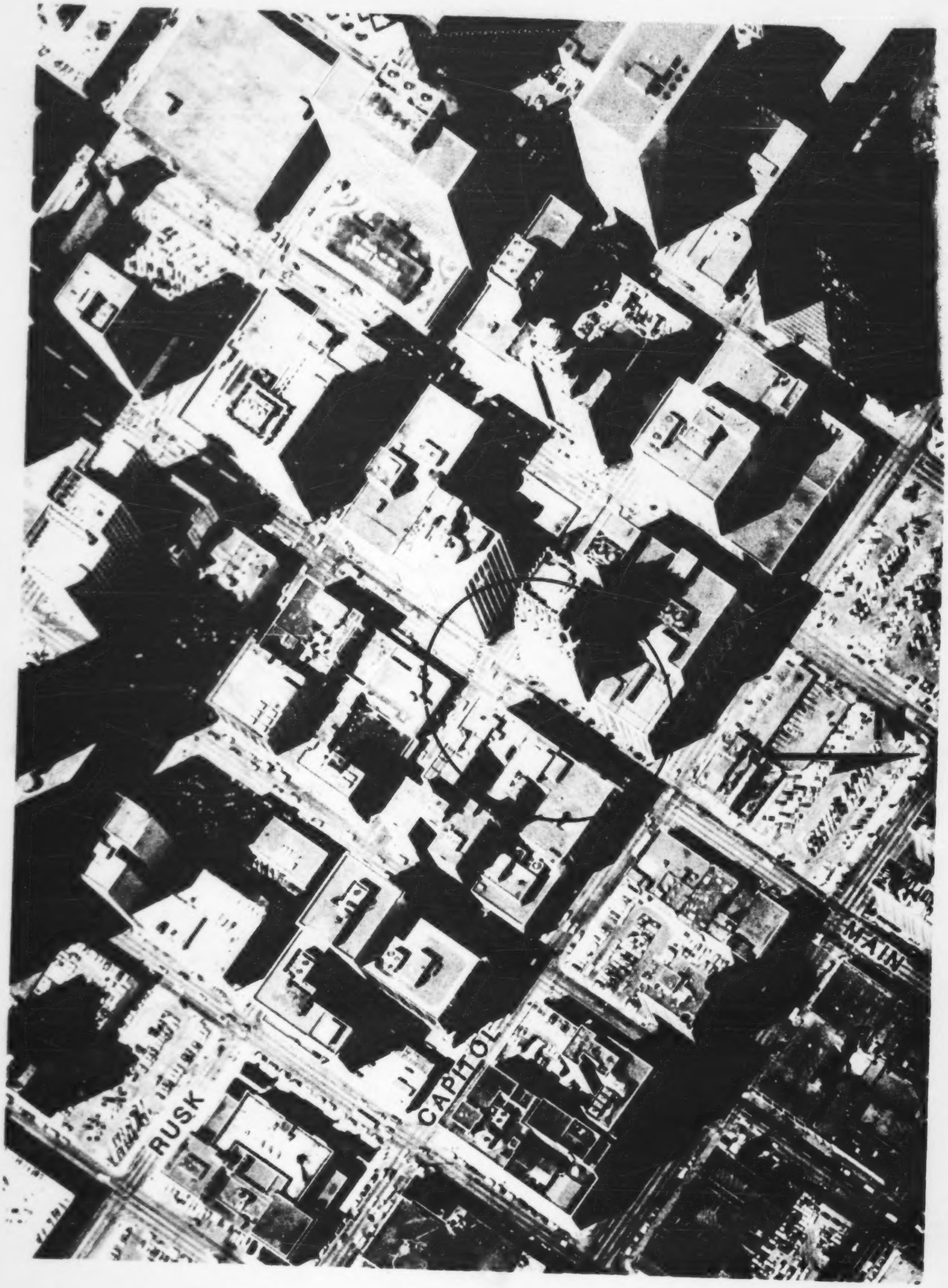

MAIN
CAPITOL
RUSK

Figure 29. Aerial View of a Portion of Downtown Houston, Texas.

Again, two assumed traffic flow and speed combinations were used, 200 vehicles per hour per lane at 5 mph, and 400 vehicles per hour per lane at 20 mph. For the six lanes of main street, the two traffic flows are 1200 vehicles per hour and 2400 vehicles per hour.

The receptor locations were the same as for the typical situation. The first, located 1.5 meters above the midpoint of the sidewalk, and the second in a vehicle in the outside leeward lane.

Using a 1 g/mile per vehicle emission factor, the total emission strength for 1200 vehicles is 2.07×10^{-4} g/sec m. The street canyon contribution to the ambient concentration experienced by a receptor at the sidewalk midpoint is:

$$C_V = \frac{(7\times10^6)(2.07\times10^{-4})}{(0.9+0.5)(11.52+2)} = \frac{7 \times 2.07 \times 10^2}{1.4 \times 13.52}$$

$$C_V = 76.55\ \mu g/m^3$$

Again, it is assumed that the background concentration caused by other vehicles in the area is equal to the street canyon contribution at 3 meters above the canyon edge of the sidewalk. For 3 meters above the sidewalk, the slant distance is 14.04 meters. The resulting concentration is 64.53 $\mu g/m^3$. The total concentration experienced by a receptor at the midpoint of the leeward sidewalk when the traffic flow is 1200 vehicles per hour is:

$$C_t = 76.6\ \mu g/m^3 + 64.5\ \mu g/m^3 = 141.1\ \mu g/m^3$$

For a receptor in a vehicle in the outside leeward lane of the street canyon, a slant distance of 7.72 meters can be assumed. The concentrations at this point, for a traffic flow of 1200 vehicles per hour are:

$$C_V = 134.07\ \mu g/m^3$$

$$C_t = 134.1 + 64.5 = 198.6\ \mu g/m^3$$

For 2400 vehicles per hour the total emission strength is 4.14×10^{-4} g/sec m. For a receptor on the upwind sidewalk, and a traffic flow of 2400 vehicles per hour, the street canyon contribution to the ambient concentration is:

$$C_V = 153.11\ \mu g/m^3$$

The background concentration from other vehicles in the area is again assumed to be equal to the street contribution at three meters above the sidewalk. The background concentration for 2400 vehicles per hour is:

$$C_b = 129.05\ \mu g/m^3$$

The total concentration for a receptor on the sidewalk with a traffic flow of 2400 vehicles per hour is:

$$C_t = 153.1 + 129.0 = 282.1\ \mu g/m^3$$

For a receptor in a vehicle in the outside leeward lane of the street canyon, and a traffic flow of 2400 vehicles per hour, the concentrations are:

$$C_V = 268.14\ \mu g/m^3$$

$$C_t = 268.1 + 129.0 = 397.1\ \mu g/m^3$$

A summary of the pertinent physical parameters and the ambient concentrations for both the typical and severe street canyon exposure situations is presented in Table 20.

3. Use of Street Canyon Concentrations With Other Emission Factors

To obtain the ambient air concentrations for these situations with other vehicle emission rates in grams/mile, simply multiply the ambient concentration obtained assuming 1 g/mile by the new emission rate.

For example, if an urban cycle CO emission rate for 1970 is taken as 85.6 g/mile then the ambient concentration on the sidewalk of the typical street canyon with 1600 vehicles per hour traffic flow would be:

$$C_V = 43.1 \times 85.6 = 3689\ \mu g/m^3 \text{ or } 3.69\ mg/m^3$$

$$C_b = 41.7 \times 85.6 = 3569\ \mu g/m^3 \text{ or } 3.57\ mg/m^3$$

$$C_t = 84.8 \times 85.6 = 7258\ \mu g/m^3 \text{ or } 7.26\ mg/m^3$$

The total ambient concentration for this location would have been approximately 7.26 mg/m^3, or 6.3 ppm CO. From the measured street canyon CO values found in the literature, this is a representative concentration for the 1970 time period.

As another example, consider the severe street canyon situation using Main Street in Houston with 2400 vehicles per hour. Again, calculate the CO emission rates for 1970:

$$C_V = 153.1 \times 85.6 = 13105\ \mu g/m^3 \text{ or } 13.11\ mg/m^3$$

$$C_b = 129.0 \times 85.6 = 11042\ \mu g/m^3 \text{ or } 11.04\ mg/m^3$$

$$C_t = 282.1 \times 85.6 = 24148\ \mu g/m^3 \text{ or } 24.15\ mg/m^3$$

The total ambient CO concentration for this location and traffic flow would have been 24.15 mg/m^3, or 21.0 ppm. This value can be compared to the maximum one hour average CO reading of 29.5 ppm (occurring at 9 am) taken by the Texas Air Control Board at Main and Capital during a survey in October 1968.

TABLE 20. STREET CANYON AMBIENT AIR CONCENTRATIONS

	Typical Situation Houston St., San Antonio, TX				Severe Situation Main St., Houston, TX			
	800 vehicles/hr		1600 vehicles/hr		1200 vehicles/hr		2400 vehicles/hr	
	Sidewalk	In-Vehicle	Sidewalk	In-Vehicle	Sidewalk	In-Vehicle	Sidewalk	In-Vehicle
1. Rooftop wind speed, m/sec	3.6	3.6	3.6	3.6	0.9	0.9	0.9	0.9
2. Rooftop wind direction relative to steeet, degrees	45-135	45-135	45-135	45-135	45-135	45-135	45-135	45-135
3. Traffic volume vehicles/hr	800	800	1600	1600	1200	1200	2400	2400
4. Emission Factor, g/vehicle mi	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5. Receptor slant distance, m	8.9	1.0	8.9	1.0	11.5	7.7	11.5	7.7
6. Concentration from vehicles in street canyon, $\mu g/m^3$	21.6	78.5	43.1	157.1	76.6	134.1	153.1	268.1
7. Estimated background, $\mu g/m^3$	20.8	20.8	41.7	41.7	64.5	64.5	129.0	129.0
8. Total concentration, $\mu g/m^3$	42.4	99.3	84.8	198.8	141.1	198.6	282.1	397.1

E. Urban Expressway Concentrations

The expressway exposures considered were of two types; the receptor in a vehicle on the expressway, and the receptor beside (within one kilometer downwind of) the expressway. For the on-expressway situation, two urban expressways were chosen to represent the typical and severe exposure situation. The ambient concentrations for a commuter in traffic were calculated using the ONEX computer program developed for this project, and explained in Section III. Since it has been shown in Section IV that all relative wind directions are equally likely when considering all urban freeways, the ambient concentrations were calculated over the 90 degree quadrant that would produce the highest ambient concentration. The concentrations were also calculated over a range of wind speeds from one to six m/sec (2.2 to 13.4 mph).

While the expressway commuter exposure is short term (less than one hour), the downwind exposures of interest are both short term and long term. Since ambient concentrations decay quickly downwind of a line source, only a severe exposure situation was investigated. In addition to the parameters covered in Section IV for a severe case expressway, the long term severe exposure situation required that the wind be perpendicular to the expressway a large portion of the year. For this reason, a different physical situation was chosen for the severe downwind exposure case than was used for the severe on-expressway situation.

1. Typical On-Expressway Concentrations

The typical exposure situation was chosen at IH 410 on the west side of San Antonio, between Valley Hi Drive and U.S. 90. This is a relatively straight, level, four lane section of urban expressway running in a SSE and NNW direction. Average daily traffic at this point is approximately 30,000 vehicles per day. The receptor was chosen as a vehicle occupant in the outside southbound lane during the morning peak traffic period.

Observation of traffic at this point showed that vehicles tended to be bunched in packs of approximately 20 cars, evenly distributed between lanes, with an average of approximately 1.5 seconds between vehicles in the same lane. The average speed was approximately 55 miles per hour. Figure 30 is a sketch of the physical situation. The complete set of input parameters for the typical exposure situation is listed below:

- Highway dimensions
  - 4 lanes, each 3.66 meters (12 feet) wide
  - median, 13.41 meters (44 feet) wide

- Vehicle volume
  - 900 vehicles per hour per lane on southbound (receptor) side
  - 500 vehicles per hour per lane on northbound side

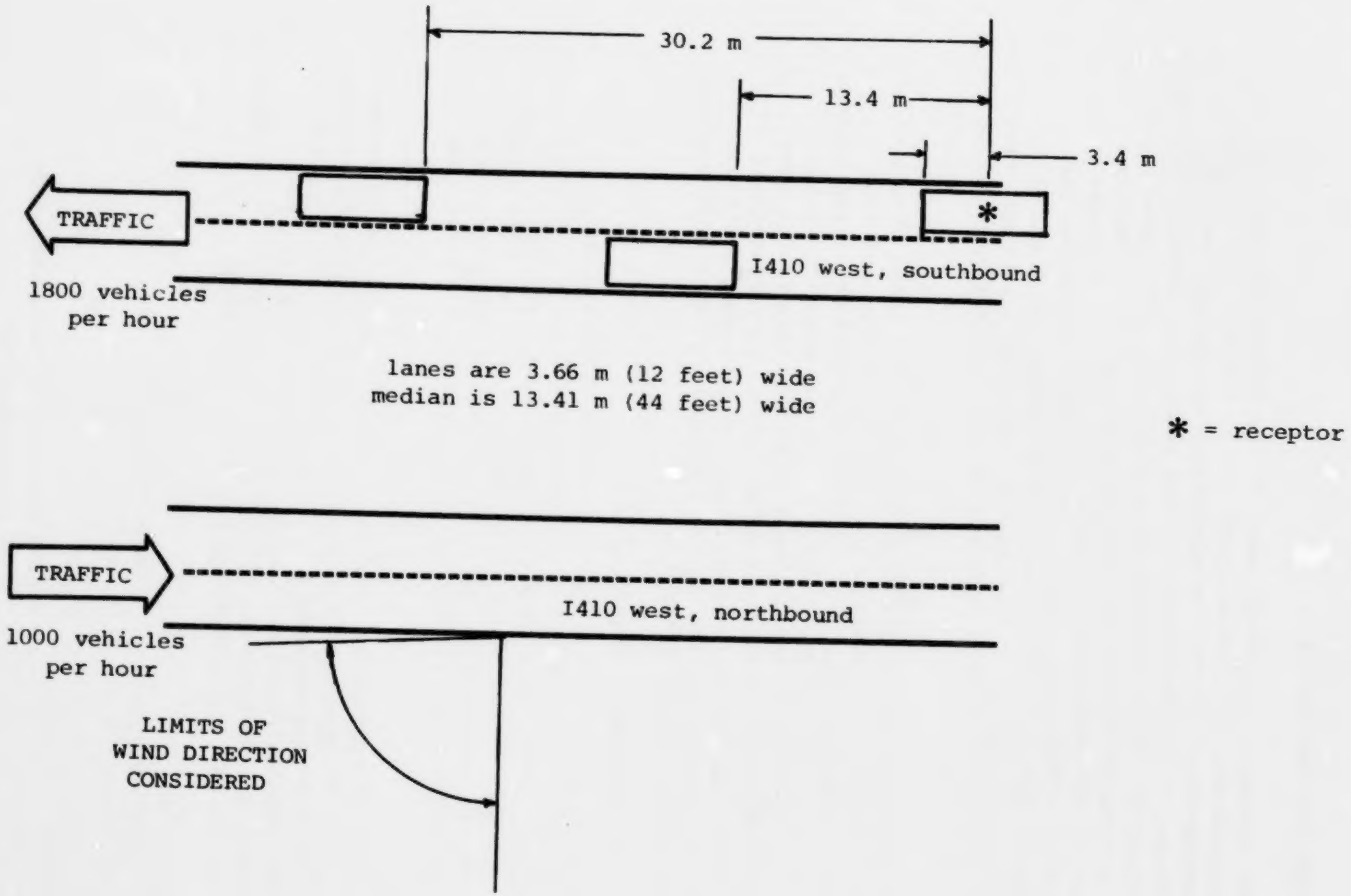

30.2 m
13.4 m
3.4 m
TRAFFIC
1800 vehicles per hour
I410 west, southbound
lanes are 3.66 m (12 feet) wide
median is 13.41 m (44 feet) wide
* = receptor
TRAFFIC
1000 vehicles per hour
I410 west, northbound
LIMITS OF WIND DIRECTION CONSIDERED

Figure 30. Sketch of expressway section for typical expressway exposure

- Point source (vehicles on receptor side) information
  - emission strength, 0.0153 g/sec, (1 g/mile at 55 mph)
  - average of four vehicle lengths between vehicles
  - average vehicle length, 6.7 miles (22 feet assumes 80 percent cars, 20 percent trucks
  - exhaust height assumed to be 0.3 meters (one foot)
  - 10 vehicles in each lane ahead of receptor vehicle
- Line source (vehicles in opposite lanes)
  - line source strength 0.0862×10^{-3} g/sec m lane (1 g/mile per vehicle, 500 vehicles per hour)
  - bouyancy flux 0.0191 m^3/sec^3
- Receptor
  - located at center of outside downwind lane
  - height 1.22 meters (4 feet)
- Meteorology
  - wind direction, from 357.5 degrees to 270 degrees relative to receptor vehicle direction
  - wind speed, from 1 to 6 m/sec (2.2 to 13.4 mph)
  - stability, Pasquill Class C (slightly unstable)

The calculated ambient concentrations are shown in Table 21 and in graphically in Figure 31. For the whole range of wind directions and speeds, the ambient concentration experienced by a receptor in the outside downwind lane varies from 61 to 124 $\mu g/m^3$.

The highest ambient concentrations occur when the wind is close to perpendicular to the road. This is because the vehicle speed is so much greater than the wind speed, that the wind direction has little effect on the relative wind speed and direction for the vehicles traveling in the same direction as the receptor. Thus the contribution from the vehicles on the receptors side of the road decreased only slightly as the wind direction changes to more perpendicular. The contribution from the vehicles traveling in the opposite direction, increase by a greater amount as the wind becomes more perpendicular, resulting in a net increase in ambient concentrations. Note however, that the wind direction for maximum concentration varies with wind speed.

2. Severe On-Expressway Concentrations

The severe expressway situation was chosen as the Santa Monica Freeway (IH 10) on the west side of Los Angeles between the cross streets of Washington and La Brea. This is a relatively, straight, level, 10 lane section of urban freeway running in a WSW to ENE direction. Average daily traffic at this point is approximately 200,000 vehicles per day. The receptor chosen was a vehicle occupant on the eastbound side of the freeway during the morning peak traffic period. Two receptors were initially used to check whether the middle or outside lane had the largest concentrations. It was determined that a receptor in the middle lane would be subject to the highest concentrations. Therefore, the concentrations presented in this section are for a receptor in the middle eastbound lane.

TABLE 21. AMBIENT CONCENTRATION FOR RECEPTOR ON EXPRESSWAY - TYPICAL EXPRESSWAY EXPOSURE SITUATION

Wind Direction Degrees Relative	Wind Speed m/sec (mph)	Outside downwind lane Ambient Concentration µg/m^3
357.5	1.0 (2.2)	120
355.0	1.0 (2.2)	120
340.0	1.0 (2.2)	122
315.0	1.0 (2.2)	124
270.0	1.0 (2.2)	122
357.5	2.0 (4.5)	114
355.0	2.0 (4.5)	113
340.0	2.0 (4.5)	109
315.0	2.0 (4.5)	103
270.0	2.0 (4.5)	95
357.5	3.0 (6.7)	109
355.0	3.0 (6.7)	107
340.0	3.0 (6.7)	99
315.0	3.0 (6.7)	85
270.0	3.0 (6.7)	77
357.5	6.0 (13.4)	96
355.0	6.0 (13.4)	92
340.0	6.0 (13.4)	75
315.0	6.0 (13.4)	61
270.0	6.0 (13.4)	72

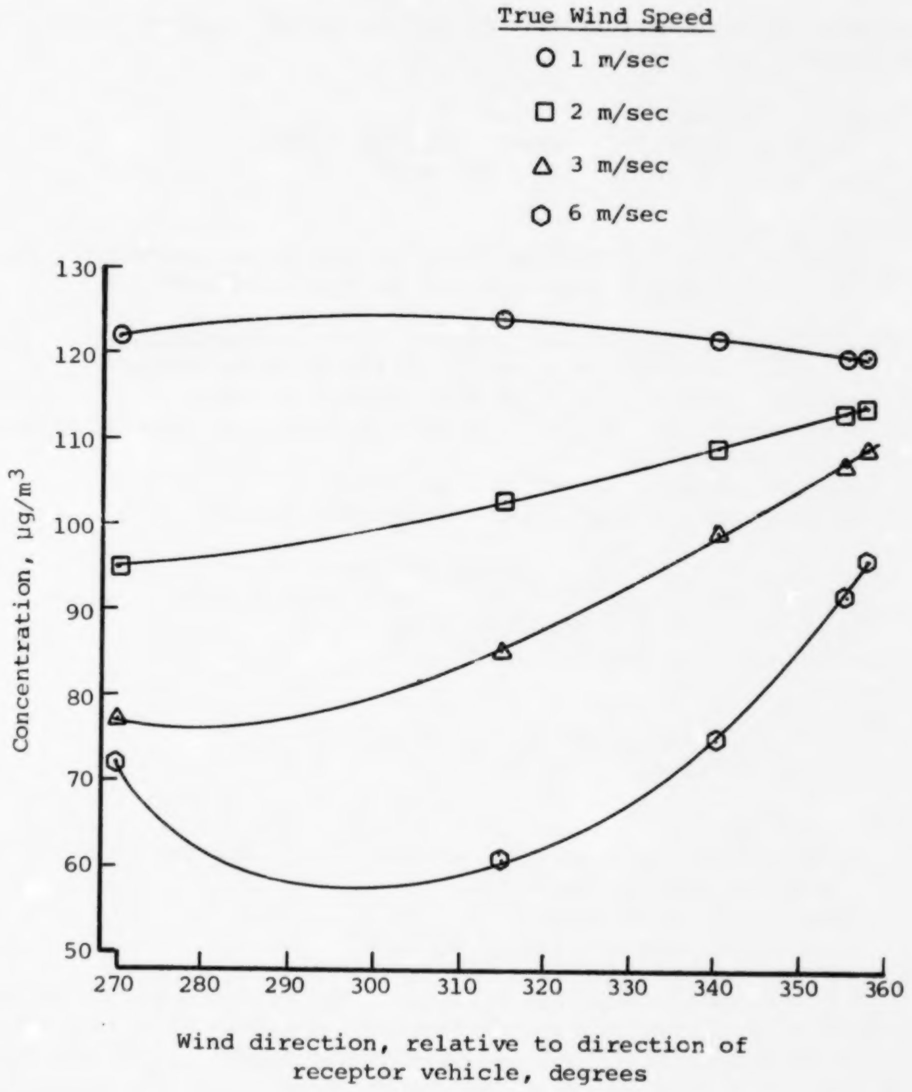


Figure 31. Ambient pollutant concentration as a function of wind direction. Typical expressway case.

Traffic counts for this section of freeway at 15 minute intervals were obtained from the District 7 Office of the California Department of Transportation along with the freeway dimensions.

The complete set of input parameters for the severe exposure situation is listed below:

- Highway dimensions
  - 10 lanes, each 3.35 meters (11 feet) wide
  - median, 6.71 meters (22 feet) wide

- Vehicle Volume
  - 2000 vehicles per hour per lane on eastbound (receptor) side
  - 1675 vehicles per hour per lane on westbound side

- Point Source (vehicles on receptor side) information
  - emission strength, 0.01389 (1 g/mile at 50 miles/hr)
  - average of two vehicle lengths between vehicles
  - average vehicle length 6.7 meters (22 feet) assumes 80 percent cars, 20 percent trucks
  - exhaust height, 0.3 meters (one foot)
  - 10 vehicles per lane ahead of receptor vehicle

- Line Source (vehicles in opposite lanes)
  - line source strength, 0.2982×10^{-3} g/sec m lane (1 g/mile per vehicle, 1675 vehicles/hr per lane)
  - bouyancy flux 0.0638 m^3/sec^3

- Receptor
  - located at center of center lane
  - height 1.22 meters (4 feet)

- Meteorology
  - wind direction, from 357.5 degrees to 270 degrees relative to receptor vehicle direction
  - wind speed, 1 to 6 m/sec (2.2 to 13.4 mph)
  - stability, Pasquill Class C (slightly unstable)

For a severe exposure situation, the wind conditions should be those that cause the highest concentrations within the range of naturally occurring conditions and within the capability of the model. It has been shown that all wind directions relative to the expressway were equally likely when all expressways in the county are considered. The highest concentrations are also caused by the lowest speed wind. For the model used, one m/sec (2.2 miles/hr) is the lowest useable speed. Therefore, for a severe exposure situation the wind will be perpendicular to the road at one m/sec. For this situation, the wind would be from the NNW at 2.2 mph. A check of the wind direction and speed matrix for Los Angeles shows that the wind is from the NNW at 0 to 3 knots (0 to 3.5 mph) approximately 0.5 percent of the time. Thus, the severe wind conditions represent a real, but uncommon, wind condition. As with the typical exposure situation, other wind direction and speeds were also investigated for comparison purposes.

As with all the microscale situations examined in this study, the emission factor per vehicle was set to one gram per mile to permit easy scaling of the results for other emission factors.

The ambient concentrations for this situation as calculated using the ONEX computer program are shown in Table 22. Note that for this situation the highest concentrations are obtained with the lowest wind speed in a direction perpendicular to the road. However, as the wind speed increases, the maximum ambient concentration shifts toward parallel with the road. This shift can be seen better in the graphical presentation of the concentrations, Figure 32. For the severe case, the concentrations at the receptor varied from 148 $\mu g/m^3$ to 506 $\mu g/m^3$.

3. Severe Beside-Expressway Concentrations

To obtain a severe situation for a receptor downwind of an expressway for both short and long term exposure, it was necessary to have a large expressway located in such a manner that the prevailing wind was perpendicular to the expressway a large part of the time.

The actual site chosen was I-10 at Silber Road on the west side of the city of Houston. At this location, I-10 runs due east and west, with four lanes in each direction. The 1977 traffic count was 167,860 vehicles per day. A sketch of this expressway section is shown in Figure 33.

An examination of the Houston wind direction data indicated that the wind is from 90 compass degrees to 270 compass degrees approximately 60 percent of the time. This means that the highway vehicle emissions will be dispersed to the north of the expressway approximately 60 percent of the time.

The severe short term exposure situation was chosen as the morning rush hour. The traffic count at this time was taken as nine percent of the ADT count, or 1890 vehicles per hour per lane.

For a severe beside-expressway situation, the wind should be perpendicular to the expressway at a speed as low as permitted by the model. The Houston wind direction data indicated that during the morning rush hour the wind was from the south between 1 and 1.54 m/sec (0 and 3.4 mph), approximately one percent of the time. The atmospheric stability was within one stability class of neutral approximately 90 percent of the time. Therefore, the severe exposure case represents a situation that does occur.

For the short term exposure, the line source portion of the ONEX exposure model was used to determine the concentrations at various distances from the north side of the expressway. The concentrations obtained from applying the model to this situation are shown in Table 23. A graphical presentation is shown in Figure 34 following the discussion of the long term exposure.

TABLE 22. AMBIENT CONCENTRATION FOR RECEPTOR ON EXPRESSWAY - SEVERE EXPRESSWAY EXPOSURE SITUATION

Wind Direction Degrees Relative	Wind Speed m/sec (mph)	Outside downwind lane Ambient Concentration µg/m^3
357.5	1.0 (2.2)	454
355.0	1.0 (2.2)	467
340.0	1.0 (2.2)	494
315.0	1.0 (2.2)	506
270.0	1.0 (2.2)	495
357.5	2.0 (4.5)	453
355.0	2.0 (4.5)	458
340.0	2.0 (4.5)	428
315.0	2.0 (4.5)	400
270.0	2.0 (4.5)	369
357.5	3.0 (6.7)	444
355.0	3.0 (6.7)	435
340.0	3.0 (6.7)	375
315.0	3.0 (6.7)	327
270.0	3.0 (6.7)	285
357.5	6.0 (13.4)	399
355.0	6.0 (13.4)	366
340.0	6.0 (13.4)	275
315.0	6.0 (13.4)	200
270.0	6.0 (13.4)	148

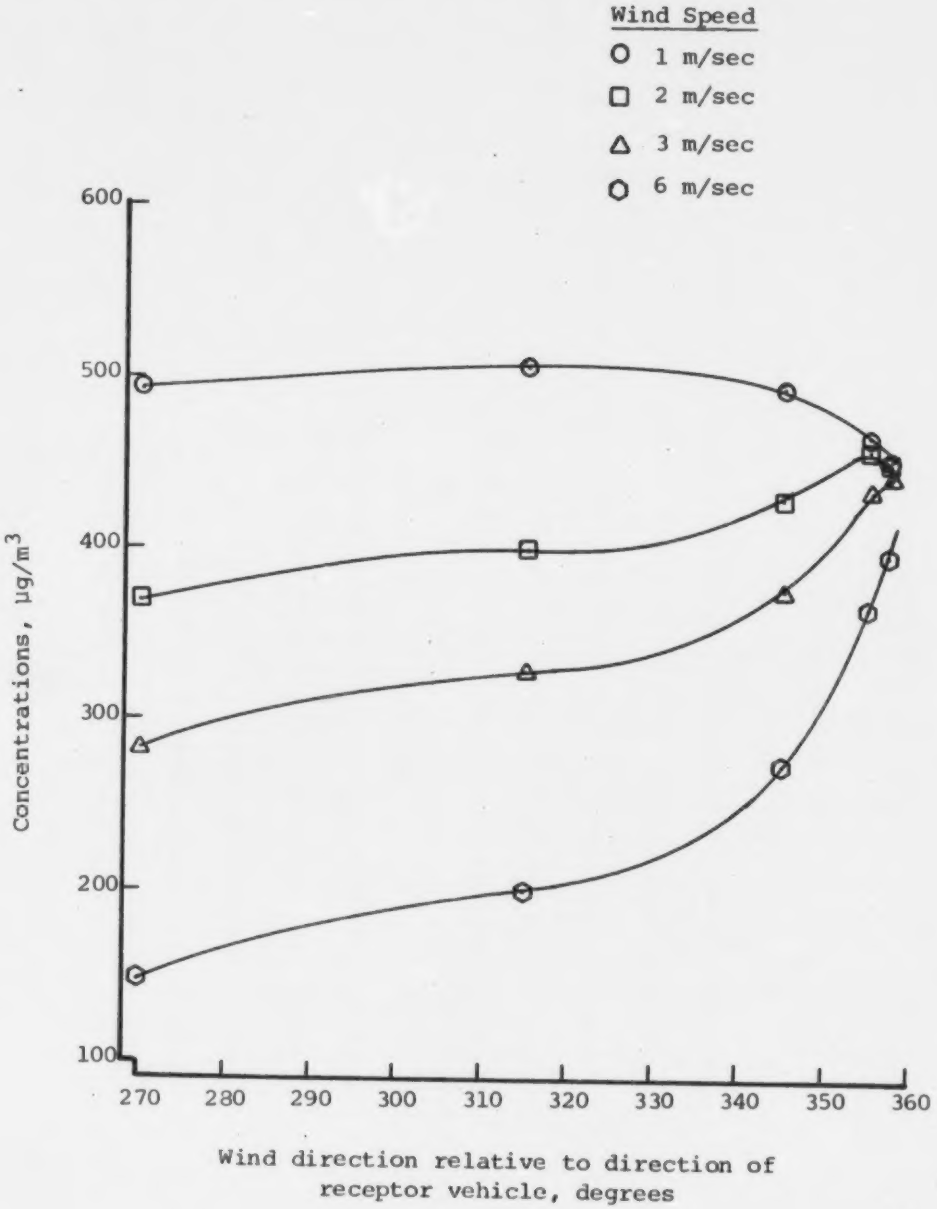


Figure 32. Concentrations experienced by receptor traveling on expressway. Severe expressway case.

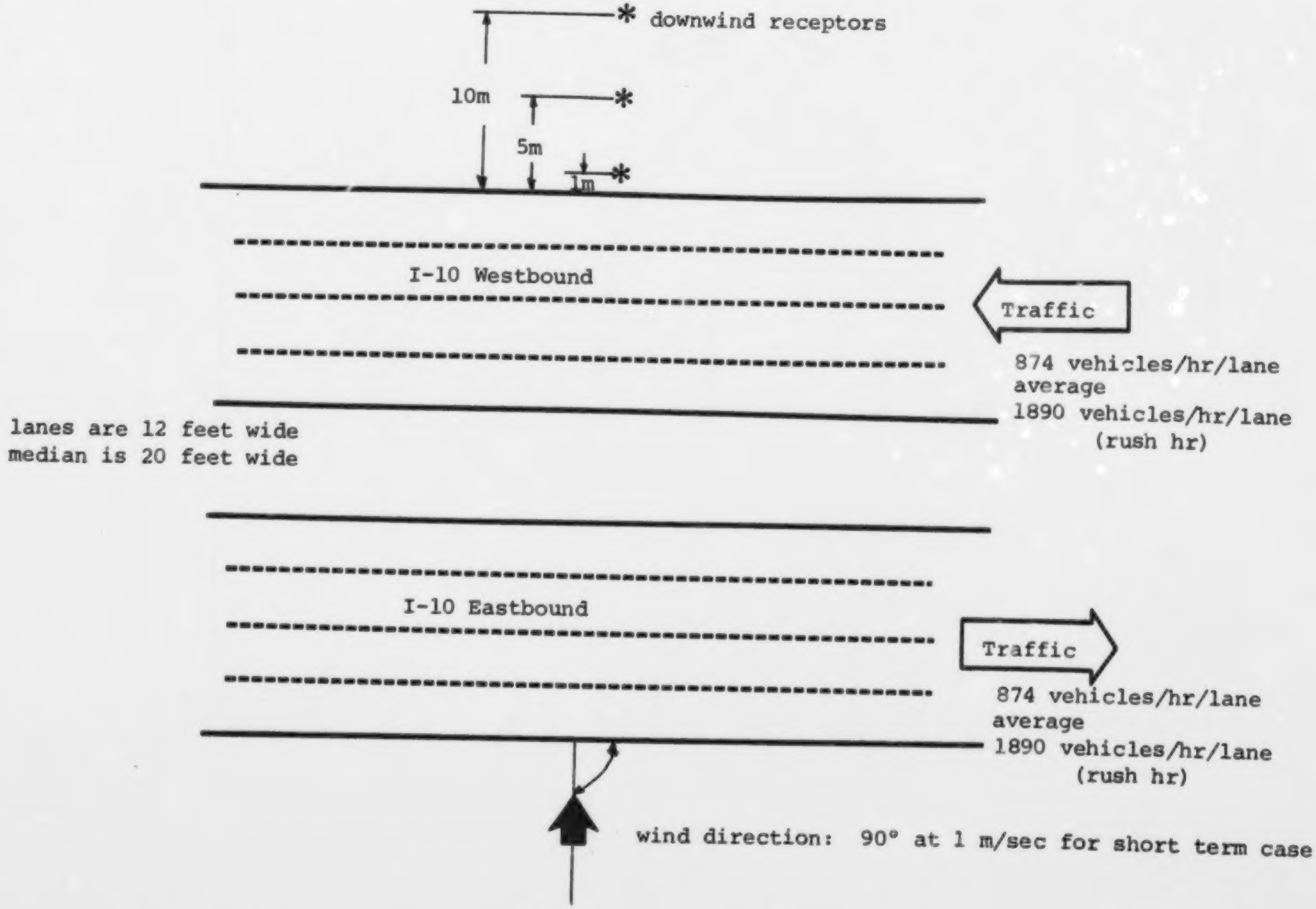

downwind receptors
10m
5m
1m
I-10 Westbound
Traffic
874 vehicles/hr/lane
average
1890 vehicles/hr/lane
(rush hr)
lanes are 12 feet wide
median is 20 feet wide
I-10 Eastbound
Traffic
874 vehicles/hr/lane
average
1890 vehicles/hr/lane
(rush hr)
wind direction: 90° at 1 m/sec for short term case

Figure 33. I-10 at Silber Road, Houston, Texas

TABLE 23. AMBIENT CONCENTRATIONS FOR A RECEPTOR DOWNWIND OF AN EXPRESSWAY

Distance downwind from road edge, meters	Ambient Concentration $\mu g/m^3$
1	397
5	368
10	334
25	248
50	171
100	105
500	26.3
1000	13.6

Site Conditions:

1. Distance from lane center to downwind road edge in meters:

   Lane 1 = 1.8, Lane 2 = 5.5
   Lane 3 = 9.1, Lane 4 = 12.8
   Lane 5 = 22.6, Lane 6 = 26.2
   Lane 7 = 29.9, Lane 8 = 33.5

2. Number of vehicles per lane per hour: 1890
3. Emissions per vehicle, g/mile 1.0
4. Emissions per lane, $\mu g/sec\ m$: 326
5. Bouyancy flux, m^3/sec^3 (per lane): 0.072
6. Wind direction relative to road: 90°
7. Wind speed: 1 m/sec
8. Stability: Neutral
9. Source height: 0.5 meters
10. Receptor height: 1.8 meters

The long-term exposure assessment is for persons living and working close to the expressway. For this study, long-term will be taken to be the annual average. Most line source dispersion models for highway vehicle emissions are for short-term (typically one hour) estimation, since wind and atmospheric stability are constant only for short periods. The problem is to obtain annual averages from the short-term models. Using a method suggested by Turner(90), H. E. Sievers of the Texas Air Control Board staff modified three line source models extensively to give annual arithmetic means.(91) The method employed involves the computation of the ambient particulate concentration for each of the 576 defined meteorological combinations (16 wind directions, times 6 stability classes, times 6 wind speed classes), then multiplying by the frequency of occurrence of each particular meteorological combination. All non-zero concentrations are then summed to obtain the annual arithmetic mean.

Fortuitously, Reference 91 contains a plot of the annual arithmetic concentrations as a function of distance from the roadway on the north side of an east-west expressway, using Houston meteorological data, assumed traffic count, and vehicle emission factors. These concentrations were generated using the Chock-G.M. line source model, the same calculations used in the ONEX model. In this model, as in all Gaussian plume models, the emission rate (the product of the grams/km/vehicle and vehicles/hr) is a multiplier to the dispersion equation. Thus, the results from Sievers' study need only to be multiplied by the ratio of the emission rate in this study to the emission rate in that study to obtain the annual arithmetic average particulate concentrations at the chosen site. The estimated annual arithmetic average particulate concentrations on the north side of I-10 at Silber Road are presented in Table 24. Figure 34 presents a comparison of the severe short-term exposure and the annual average exposure for all wind conditions.

4. Use of Expressway Concentrations With Other Emission Factors

To illustrate the use of the expressway exposure results and to put them in the context of a commonly measured pollutant, the CO concentration experienced by the receptor in each of the expressway situations will be calculated.

For the typical on-expressway exposure case in San Antonio, the current CO emission factor is assumed to be 50 g/mile at 55 mph. The CO concentration at the most severe wind condition is then:

$$124\ \mu g/m^3 \times 50 = 6200\ \mu g/m^3 \text{ or } 5.4 \text{ ppm CO}$$

For the severe on-expressway exposure case in Los Angeles, the current CO emission factor is assumed to be 50 g/mile at 50 mph. The CO concentration at the most severe wind condition is then:

$$506\ \mu g/m^3 \times 50 = 25{,}300\ \mu g/m^3 \text{ or } 22.0 \text{ ppm CO}$$

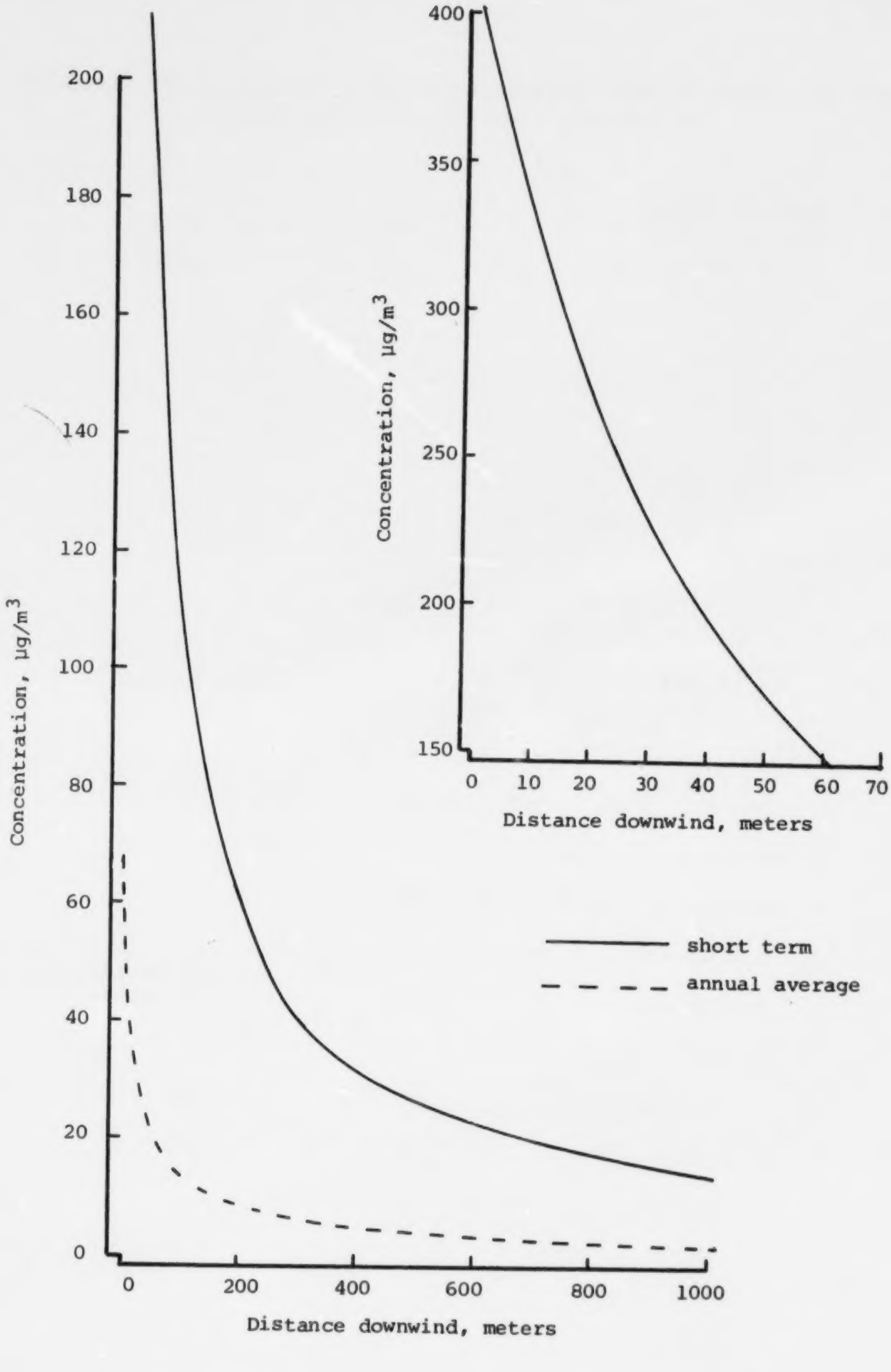


Figure 34. Concentrations downwind of expressway

TABLE 24. ANNUAL AVERAGE CONCENTRATIONS FOR A RECEPTOR ON THE NORTHSIDE OF I-10 AT SILBER ROAD, HOUSTON, TEXAS

Distance downwind from road edge, meters	Ambient Concentration µg/m^3
1	61
5	55
10	48
25	35
50	23
100	14
500	4
1000	1.6

Site Conditions:

1. Distance from lane center to downwind road edge in meters:

   Lane 1 = 1.8, Lane 2 = 5.5
   Lane 3 = 9.1, Lane 4 = 12.8
   Lane 5 = 22.6, Lane 6 = 26.2
   Lane 7 = 29.9, Lane 8 = 33.5

2. Number of vehicles per lane per hour: 874
3. Emissions per lane, g/sec m: 150.9
4. Bouyancy flux,m^3/sec^3 (per lane): 0.033
5. Wind direction relative to road:
6. Wind Speed:
7. Stability:

   } 10 year average of observation by time of day

8. Source height: 0.5 meters
9. Receptor height: 1.8 meters

A 1977 study measured the CO level inside a moving vehicle on the Santa Monica Freeway at 10 am in April 1977.(92) For a 55 mph traffic speed, the CO level inside the car was approximately 5 ppm. A recent British study measured CO concentrations in traffic, both inside and outside a moving vehicle.(93) In expressway type driving, internal vehicle CO levels of 10 ppm were common. The ratio of inside to outside concentrations for 11 cars ranged from 0.35 to 0.75. Applying the minimum ratio to both studies referenced above would give expressway CO concentrations of between 15 and 30 ppm. Thus, the calculated severe case CO concentration of 22 ppm is in agreement with the measured values.

To obtain ambient CO concentrations for the short-term beside-expressway situation, a 1979 CO emission factor of 75 g/mile is assumed. The concentrations with distance are then:

5 meters: 352 × 75 = 26,400 $\mu g/m^3$ or 23 ppm CO
10 meters: 334 × 75 = 25,800 $\mu g/m^3$ or 22 ppm CO
50 meters: 171 × 75 = 12,825 $\mu g/m^3$ or 11 ppm CO
100 meters: 105 × 75 = 7,875 $\mu g/m^3$ or 7 ppm CO
500 meters: 26.3 × 75 = 1,972 $\mu g/m^3$ or 2 ppm CO

The long-term CO concentrations, assuming the same CO emission factors, are:

5 meters: 55 × 75 = 4,125 $\mu g/m^3$ or 3.6 ppm CO
10 meters: 48 × 75 = 3,600 $\mu g/m^3$ or 3.1 ppm CO
50 meters: 27 × 75 = 2,025 $\mu g/m^3$ or 1.8 ppm CO
100 meters: 14 × 75 = 1,050 $\mu g/m^3$ or 0.9 ppm CO
500 meters: 4 × 75 = 300 $\mu g/m^3$ or 0.3 ppm CO

F. Localized Area Concentrations

The one localized area for which some information was available was parking lots. Sizeable parking lots occur at facilities such as shopping malls and sports stadiums. Despite the apparent possibility of high ambient air concentration of automotive pollutants in parking lots, EPA studies have shown that this is not the case.(96,94) The referenced studies measured CO in a shopping mall parking lot and in sports stadium parking lots, respectively. The one hour CO concentration in the shopping mall parking lot never exceeded 13 ppm, and 90 percent of the time it was less than 5 ppm.

The sports stadiums, which of course were event-oriented, had higher CO levels. In Reference 95, CO was measured before and after several baseball games at Threerivers Stadium (Pittsburgh) and Atlanta Stadium. At both stadiums the highest CO levels were recorded approximately one-half hour after end-of-game. In Pittsburgh, the highest CO measured in 15-minute bagged samples around the stadium and in the stadium parking lots was 23.5 ppm. This value is about 22 ppm above the usual background.

In Atlanta, the highest 15-minute bagged reading was 50.5 ppm, or about 45 ppm above the post-game background. The Atlanta reading was taken on the sidewalk next to the main egress street for the stadium. This situation should probably be classed as a roadway exposure rather than a parking lot exposure. Other bag samples taken farther away from streets, in the area of the stadium entrances, never exceeded 9 ppm CO.

Thus, parking lots do not appear to produce levels of automotive pollutants as high as the other microscale situations examined. Should some pollutant be found that would affect health at these low levels, it would be necessary to develop a dispersion model for this source type and expend further effort in defining the magnitude of the exposure occurrence on a national basis.

VI. RECOMMENDATIONS

During the course of this study, a number of deficiencies in available information were found. If the approach taken in this project for evaluating the possible health and welfare effects of unregulated pollutants is to be developed further, several areas need additional study. From the experience gained during this project, the following are recommendations for further study:

1. Enclosed Space Dispersion Model - The enclosed space model utilized in this study is not well developed. At the least, a thorough study of the effective ventilation factor is required. A better solution would be the development of a new model using the ventilation flow patterns within an enclosed space, and the fundamental fluid dynamics equation for dispersion of the pollutant.

2. Tunnel Dispersion Model - A model for pollutant dispersion within a tunnel considering the fundamental fluid dynamics equaltions has been developed. This model, TUNVEN, is recommended for all future work involving tunnel pollutant concentrations.

3. Street Canyon Dispersion Model - Since it is likely that very deep street canyons will have higher pollutant levels than typical street canyons, a dispersion model for deep street canyons is needed. It is recommended that a dispersion model be developed for street canyons having height to width ratios greater than 2.0.

4. On Expressway Dispersion Model - The dispersion model created for the on expressway situation in this study needs additional work. In particular, it is recommended that further study be done on the value of the dispersion coefficients in traffic.

5. Localized Source Dispersion Model - No model was found for concentrations within (as opposed to downwind of) an area source. It is recommended that such a model be developed.

6. Street Canyon Description - The range of physical variables for existing street canyons is not well defined. It is recommended that further information be collected on street canyon statistics. Such information should include number of miles by height to width ratio and by traffic density.

7. Localized Area Description - In addition to parking lots (downtown, shopping center, and sports stadiums), other area sources can be envisioned. These include truck terminals, industrial areas, and construction sites. No compiled statistics were found on these sites. If it is determined that these sites do constitute an exposure situation requiring concentration estimates, considerable effort will be needed to properly define the range of physical variables needed for a dispersion model.

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APPENDIX A

VERIFICATION OF ONEX COMPUTER PROGRAM

VERIFICATION OF ONEX COMPUTER PROGRAM

A study was conducted to check the ability of the ONEX model to predict actual on-the-road concentrations. Data from the G.M. Sulfate Experiment were used for this study.(A1) In-car sulfate measurements were taken in six cars on 15 days of the experiment. The reader is referred to Reference A1 for a complete description of the G.M. Sulfate Experiment. The cars were not always the same six vehicles nor were they always in the same position in the pack of cars. These measured in-car sulfate concentrations were compared with concentrations calculated using the ONEX computer program. The in-car sulfate concentrations can be greatly influenced by the cars immediately ahead of the receptor car. Therefore, an attempt was made to estimate the sulfate emissions on a car by car basis. To accomplish this, sulfate emissions measured from chassis dynamometer tests run during the experiment, were used to obtain estimates of the sulfate emissions for each make and model of test vehicle. A list of the make and model of each vehicle in the G.M. experiment by pack number and location in the pack was obtained from Dr. S. Cadle at General Motors Research. The dynamometer sulfate emissions by make and model were then used for the point source portion of ONEX. The measured dynamometer sulfate emissions were considered as average for the vehicle model. The dynamometer emission rate was adjusted for each day, using the ratio of the daily fleet emission rate to the average fleet emission rate for all days as calculated from measured ambient sulfates.

The emission rate for line source portion of the program was calculated from the average fleet emission rate and the number of vehicles and vehicle speed as given in Reference A1. The meteorological conditions used were the average of those measured during each day of testing as presented in Reference A1. The emission source height was set at one half meter and the receptor height at 1.2 meters.

Since the sulfate emissions for each car were not precisely known, the calculated concentrations from each vehicle were averaged for each day. In addition, the calculated sulfate value for each pack position for which sulfate measurements were available was averaged for all days. Measured concentrations were not always available for each pack position used (position 2, 3, 5, 6, 8 and 10) for each of the 14 days of the experiment used in this evaluation. Where the measured concentration for a vehicle was not available, the calculated concentration was not used in the average.

Table A1 and A2 presents the results of the ONEX program calculations together with the measured sulfate values for comparison. Figure A1 presents these comparisons graphically.

Both daily averages of all positions and position averages for all days are shown. For 10 of the 14 days of data used, the difference between calculated and measured sulfate concentrations was less than 20 percent. The agreement between measured and calculated sulfate levels indicate that the on-expressway model is adequate for the purposes of this project.

TABLE A1. COMPARISON OF MEASURED AND CALCULATED IN-CAR SULFATE CONCENTRATIONS BY TEST DAY

Avg. Wind Direc.(deg)	Avg. Wind Speed(m/sec)	Day	Avg. Meas. Conc.($\mu g/m^3$)	Avg. Calc. Conc.($\mu g/m^3$)
291.45	2.81	274	2.64	2.8
335.75	1.81	275	3.88	4.25
221.7	2.55	276	5.23	4.30
250.28	1.31	279	4.8	4.06
59.25	1.51	281	3.0	3.52
196.65	2.56	286	5.53	4.62
61.06	2.23	290	2.15	3.15
271.8	2.05	293	2.67	2.98
223.35	1.41	294	3.04	2.65
		Avg. 274-294	3.66	3.59
45.8	0.51	295	4.28	2.96
183.83	2.86	296	2.00	3.14
180.45	2.83	297	--	--
199.65	2.18	300	3.33	3.80
350.88	2.6	302	5.25	3.18
354.92	1.28	303	4.25	4.63
		Avg. 295-303	3.82	3.54

TABLE A2. COMPARISON OF MEASURED AND CALCULATED IN-CAR SULFATE CONCENTRATION BY PACK POSITION

Position	Avg. Meas. Conc.($\mu g/m^3$)	Avg. Calc. Conc.($\mu g/m^3$)
2	2.17	2.52
3	2.91	3.02
5	3.47	3.59
6	3.83	3.87
8	6.60	5.00
10	6.06	4.01

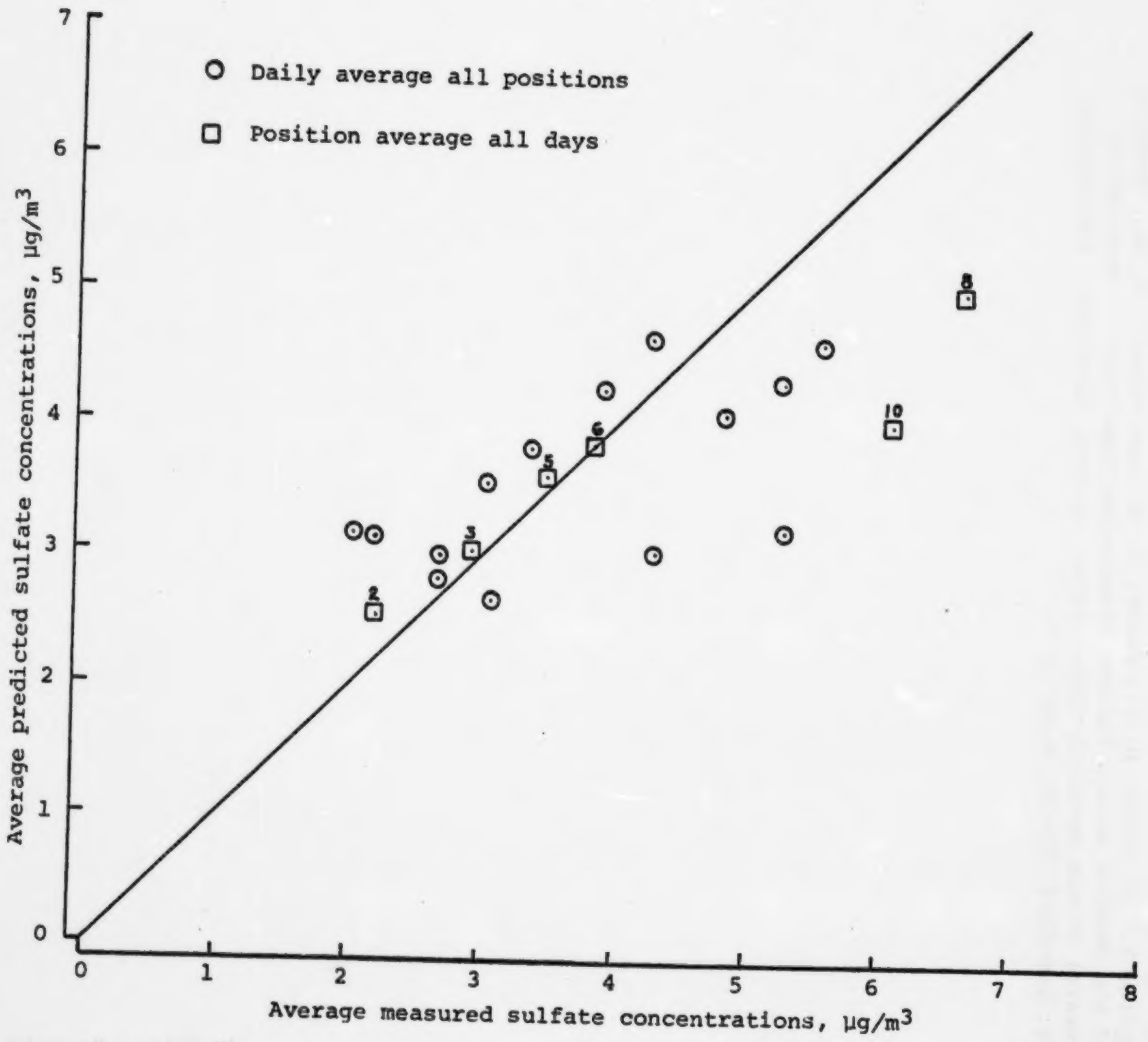

Figure A1. Comparison of measured in-car sulfate concentrations to concentrations predicted by ONEX computer program for G,M, sulfate experiment data

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APPENDIX B

TUNNELS IN THE UNITED STATES

TUNNELS IN THE UNITED STATES

STATE	NAME AND LOCATION	OPERATOR	DATE OPENED	LENGTH PORTAL TO PORTAL Ft	LENGTH PORTAL TO PORTAL M	TUBES	LANES/ TUBE	ADT	VENT(a)	ADT/LANE
Ala.	**BANKHEAD.** U.S. 90 under Mobile River; Mobile.	Ala. Highway Department	1941	3109	948	1	2	10,000	V	5,000
	WALLACE. I-10 under Mobile River; Mobile.	Ala. Highway Department	1973	3000	914	2	2	22,000	S	5,500
Ariz.	**MULE PASS.** U.S. 80 between Benson and and Douglas		1958	1400		1	3			
	QUEEN CREEK. U.S. 60, 70 between Superior and Miami		1953	1200		1	3			
Calif.	**BROADWAY.** Broadway between Hyde and Mason Sts.; San Francisco	City of San Francisco	1952	1616	493	2	2	28,500	L	7,125
	CALDECOTT. Cal. Route 24 at Contra Costa-Alameda Cnty. line; Oakland	Calif. Div. of Highways	1937 1965	3610 3371	1100 1027	2 1	2 2	50,000 50,000	T	16,667
	COLLIER. U.S. 199 near Oregon state line; Del Norte County	Calif. Div. of Highways	1963	1835	559	1	2		S	
	POSEY. Cal. Route 260 under Oakland Estuary; Oakland	Calif. Div. of Highways	1928	3545	1081	1	2	24,500	T	12,250
	WEBSTER ST. Cal. Route 260 under Oakland Estuary (Companion to Posey)	Calif. Div. of Highways	1963	3350	1021	1	2	24,500	T	12,250
	LAKEWOOD BLVD. Cal. 19 under Long Beach Airport Runway; Long Beach	City of Long Beach	1958	908	277	2	3		S	
	SPRING ST. Spring Street under Long Beach Airport Runway; Long Beach	City of Long Beach	1958	1080	329	2	2		S	
	SECOND STREET. Second Street between Figueroa and Hill Sts.; Los Angeles	City of Los Angeles	1924	1502	458	1	4		L	
	SEPULVEDA BLVD. Cal. 1 under L. A. Internat'l. Airport runway; L. A.	City of Los Angeles	1953	1908	582	2	3	54,400	T	9,067
	THIRD STREET. Third Street between Flower and Hill Sts., Los Angeles	City of Los Angeles	1901	1059	323	1	2		L	
	WALDO. No. of Golden Gate on U.S. 101 Parallel Bore		1937 1956	1000 1000		1 1	3 3			
	ELEPHANT BUTTE. Feather River Canyon near Plumas		1937	1187		1	2			
	UNDERPASS. U.S. 40 in Newcastle		1932	531		1	2			
	UNDERPASS. Sepulveda under Mullholland in Los Angeles		~1930	655		1	3			

TUNNELS IN THE UNITED STATES (Cont'd)

STATE	NAME AND LOCATION	OPERATOR	DATE OPENED	LENGTH PORTAL TO PORTAL Ft	LENGTH PORTAL TO PORTAL M	TUBES	LANES/ TUBE	ADT	VENT(a)	ADT/LANE
Calif.	FIGUEROA ST. Los Angeles		~1936	755		1	3			
	WAWONA. Yosemite Nat'l Park		1933	4233		1	2			
	BIG OAK FLAT. Yosemite Nat'l Park		1940	2167		1	2			
	BROADWAY LOW LEVEL. State highway 24 in Oakland		1937	2944		2	2			
	PRESIDIO PARK. San Francisco		~1940	1300		1	4			
	YERBA BUENA. Yerba Buena Island San Francisco Bay		1936	514		1	10			
Colo.	EISENHOWER. I-70 under continental Divide; 60 mi. W. of Denver	Colo. Dept. of Highway	1973 1st 1979 2nd Tube	8941		2	2	8,200	S	
	MESA VERDE. Entrance to Mesa Verde Nat'l Park		1957	1470		1	2			
	STAPLETON. I-70 East of Denver under Stapleton Airport Runway	Colo. Dept. of Highway	1965	757		2	3	66,000		
	CLEAR CREEK #1. U.S. 6 West of Golden	Colo Dept. of Highway	1952	859		1	2	4,700	U	
	CLEAR CREEK #2. U.S. 6 West of Golden	Colo. Dept. of Highways	1952	1069		1	2	4,600	U	
	CLEAR CREEK #3. U.S. 6 West of Golden	Colo. Dept. of Highways	1952	726		1	2	4,600	U	
	CLEAR CREEK #6. U.S. 6 East of Idaho Springs	Colo. Dept. of Highways	1952	588		1	2	2,700	U	
	HORSESHOE (No Name). I-70 East of Glenwood Springs	Colo. Dept. of Highways	1965	1044		2	2	5,100		
	IDAHO SPRINGS. I-70 near Idaho Springs	Colo. Dept. of Highways	1961	665 EB 725 WB		2	2	14,900		
Conn.	WEST ROCK. Wilbur Cross Pkwy. (Route 15); New Haven	Conn. Dept. of Transportation	1949	1200	366	2	2	31,000	L	7,750
D. C.	CENTER LEG. I-395 under the Mall, Washington.	D. C. Dept. of Transportation	1973	3400	1036	2	4	58,000 (c)	T	7,250
	DUPONT CIRCLE. Connecticut Ave. under Dupont Circle; Washington	D. C. Dept. of Transportation	1950	578	176	2	2	27,000	L	
	9TH STREET. 9th Street under the Mall; Washington	D. C. Dept. of Transportation	1971	1610	491	1	3	14,000	S	4,667
	12TH STREET. 12th Street under the Mall; Washington	D. C. Dept. of Transportation	1964	729	222	1	3	22,000	L	

TUNNELS IN THE UNITED STATED (Cont'd)

STATE	NAME AND LOCATION	OPERATOR	DATE OPENED	LENGTH PORTAL TO PORTAL Ft	LENGTH PORTAL TO PORTAL M	TUBES	LANES/ TUBES	ADT	VENT(a)	ADT/LANE
D. C.	ZOO. Rock Creek Park		1964	800		1	2			
Fla.	NEW RIVER. U.S. 1 under New River; Fort Lauderdale	Fla. Dept. of Transportation	1960	800	244	2	2	44,000	L	
Hawaii	WILSON. Kalihi Valley; Honolulu, Oahu State road 63	City & County of Honolulu	1960	2780	847	2	2	35,000	V	8,750
	NUUANU. Pali #1, state road 61 Oahu		1957	1080		1	2			
	NUUANU. Pali #2, state road 61 Oahu		1957	500		1	2			
La.	BELLE CHASSE. State Route 31 under Intracoastal Waterway; Algiers	La. Dept. of Highways	1956	800	244	1	2		S	
	HARVEY. Bus. U.S. 90 under Intracoastal Waterway; Harvey	La. Dept. of Highways	1957	1080	329	2	2		S	
	HOUMA. State Route 3040 under Intracoastal Waterway; Houma	La. Dept. of Highways	1961	960	293	1	2		L	
Md.	BALTIMORE HARBOR. Under Patapsco River; Baltimore	Md. Dept. of Transportation	1957	7650	2332	2	2	65,500	T	16,375
Mass.	DEWEY SQUARE. John Fitzgerald Expwy. under Dewey Sq.; Boston	Mass. Dept. of Public Works	1958	2400	732	2	3	125,000	L	20,833
	CALLAHAN. U.S. 1 under Boston Inner Harbor; Boston	Mass. Turnpike Authority	1962	5070	1545	1	2	65,000	V	32,500
	SUMNER. U.S. 1 under Boston Inner Harbor (Companion to Callahan)	Mass. Turnpike Authority	1934	5657	1724	1	2	65,000	T	32,500
	PRUDENTIAL CENTER. Mass. Turnpike under Prudential Center; Boston	Mass, Turnpike Authority	1964	1980	604	2	4		L	
Mich.	DETROIT-WINDSOR. Under Detroit River betw. U.S. and Canada	Detroit-Canada Corporation	1930	5130	1564	1	2		T	
Minn.	LOWRY HILL. 1-94 under Lyndale and Hennepin Aves.; Minneapolis	Minn. Dept. of Highways	1971	1496	456	2	3	32,000 (c)	S	5,333
Nev.	CARLIN. I-80			1993						
N. J.	G. W. BRIDGE APPROACHES. East and West tunnels on approaches to G. W. Bridge	Port Authority of N.Y. & N.J.	1962	631 547	192 167	1	2		V	

TUNNELS IN THE UNITED STATES (Cont'd)

STATE	NAME AND LOCATION	OPERATOR	OPENED	PORTAL TO PORTAL Ft	PORTAL TO PORTAL M	TUBES	LANES/ TUBE	ADT	VENT(a)	ADT/LANE
N. Y.	LINCOLN. Under Hudson Rvr. betw. N.Y.C. & Weehawken, N.J.	Port Authority of N.Y. & N.J.	1937 1945 1957	8216 7482 8006	2504 2281 2440	1 1 1	2 2 2		T	15,833
	BATTERY PARK. Under Battery Park In Manhattan; New York City	New York City	1951	2400	732	2	2		S	
	FIRST AVENUE. 1st Avenue under U.N. Plaza; New York City	New York City	1953	1378	420	2	2		S	
	HUGH GRANT CIRCLE. I-95 under Hugh Grant Grant Circle, Bronx; N.Y.C.	New York City	1955	700	213	2	3			
	PARK AVENUE. Park Avenue between 33rd & 40th Streets; N.Y.C.	New York City	(b)	1392	424	1	2			
	BROOKLYN-BATTERY. Under East River betw. Manhattan & Bklyn.; N.Y.C.	Triborough Bridge & Tunnel Authority	1950	9117	2779	2	2	40,000	T	10,000
	QUEENS-MIDTOWN. Under East River betw. Manhattan & Queens; N.Y.C.	Triborough Bridge & Tunnel Authority	1940 1940	6272 6414	1912 1955	1 1	2 2	30,000 30,000	T	15,000
	HOLLAND. Under Hudson Rvr. betw. N.Y.C. & Jersey City, N.J.	Port Authority of N.Y. & N.J.	1927 1927	8558 8371	2608 2551	1 1	2 2	30,000 30,000	T	15,000
	CROSS TOWN. 178 St. N.Y.C.			2414						
	F.D. ROOSEVELT DR. 81-89 St. N.Y.C.			2400		2	3			
	F.D. ROOSEVELT DR. 42-48 St. N.Y.C.			1600		2	3			
N. C.	BEAUCATCHER. Through Beucatcher mountain, Asheville		1929	1100		1	2			
	TUNNEL #1 (Eastbound). I-40 along Pigeon River		1969	1043		1	2			
	TUNNEL #1 (Westbound). Companion to Tunnel #1 (eastbound)		1969	1119		1	2			
	TUNNEL #2. I-40 along Pigeon River		1969	1198		1	2			
Ohio	LYTLE PARK. I-71 under Lytle Park; Cincinnati	City of Cincinnati	1970	850	259	2 1	3 1		L	

TUNNELS IN THE UNITED STATES (Cont'd)

STATE	NAME AND LOCATION	OPERATOR	DATE OPENED	PORTAL TO PORTAL Ft	PORTAL TO PORTAL M	TUBES	LANES/ TUBE	ADT	VENT(a)	ADT/LANE
Ore.	KNOWLS CREEK. Love Co.			1430						
	ARCH CAPE. U.S. 101, Oregon Coast Highway		1937	1228		1	2			
	ELK CREEK. State Highway 58 Underpass		1932	1085		1	2			
	VISTA RIDGE. U.S. 26 in Portland		1970	1100		2	3			
Pa.	FORT PITT. I-79 under Mount Washington; Pittsburgh	Pa. Dept. of Transportation	1960	3600	1097	2	2	78,000	S	19,500
	LIBERTY. Under Mt. Washington betw. W. Liberty Ave. & Liberty Bridge; Pittsburgh	Pa. Dept. of Transportation	1924	5690	1734	2	2	50,000	L	12,500
	SQUIRREL HILL. I-376 under Squirrel Hill; Pittsburgh	Pa. Dept. of Transportation	1953	4225	1288	2	2	83,000	S	20,750
	ALLEGHENY. Pa. Turnpike under Allegheny Mt.; Somerset Co.	Pa. Turnpike Commission	1940 1965	6070 6070	1850 1850	2	2	18,800	S	4,700
	BLUE MOUNTAIN. Pa. Turnpike under Blue Mt.; Franklin Co.	Pa. Turnpike Commission	1940 1968	4339 4339	1323 1323	2	2	11,100	S	2,775
	LEHIGH. Pa. Turnpike. N.E. extension; Lehigh Co.	Pa. Turnpike Commission	1957	4380	1335	1	2	12,000		6,000
	KITTATINNY. Pa. Turnpike under Kittatinny Mt.; Franklin Co.	Pa. Turnpike Commission	1940 1968	4727 4727	1441 1441	2	2	11,100	S	2,775
	TUSCARORA. Pa. Turnpike under Tuscarora Mt.; Frnaklin Co.	Pa. Turnpike Commission	1940 1968	5326 5326	1623 1623	2	2	11,200	S	2,800
	EVANS. Pa. Turnpike		1957	4379		1	2			
	ARMSTRONG HILL. Pittsburgh		Unk.	1325		2	2			
R. I.	CONVERTED STREETCAR. Providence		1955	1793		1	2			
Tenn.	McCOLLIE AVE. Through Missionary Ridge in Chattanoga		1913 1955	933 1001		1 1	2 2			
	BACHMAN. U.S. 41 in Chattanoga		1929	1027		2	2			
	WILCOX. Chattanoga		Unk.	1312		1	2			

TUNNELS IN THE UNITED STATES (Cont'd)

STATE	NAME AND LOCATION	OPERATOR	DATE OPENED	PORTAL TO PORTAL Ft	PORTAL TO PORTAL M	TUBES	LANES/ TUBE	ADT	VENT(a)	ADT/LANE
Tex.	BAYTOWN-LA PORTE. SH 146 under Houston ship Channel betw. Baytown & LaPorte	Texas Dept. of Highways	1953	3009	917	1	2	20,000	S	10,000
	WASHBURN. Federal Rd. under Houston Ship Channel betw. Pasadena and Galena Park	City of Houston	1950	2936	895	1	2	27,000	S	13,500
	AIRPORT UNDERPASS. Dallas, Ft. Worth Airport		1963	813		2	3			
Utah	COPPERFIELD. Bingham Canyon, Southwest of Salt Lake City		1939	7000		1	1			
	ZION NAT'L PARK. State Road 15 in. Zion Nat'l Park		1936	5766		1	2			
Va.	BIG WALKER. I-77 under Big Walker Mt.; near Wytheville	Va. Dept. of Highways & Transp.	1972	4230	1289	2	2	1,600 (c)	T	400
	HAMPTON ROADS. I-64 under Hampton Roads Harbor betw. Norfolk & Hampton	Va. Dept. of Highways & Transp.	1957	7479	2280	1	2	22,400	T	11,200
	DOWNTOWN. U.S. 460A under Elizabeth Rvr. betw. Norfolk & Portsmouth	Va. Dept. of Highways & Transp.	1952	3350	1021	1	2	25,000	S	12,500
	MIDTOWN. U.S. 58 under Elizabeth Rvr. betw. Norfold & Portsmouth	Va. Dept. of Highways & Transp.	1962	4194	1278	1	2	16,000	T	8,000
	BALTIMORE CHANNEL. Under north ship channel; Chesapeake Bay	Chesapeake Bay Brdge. & Tun. Dist.	1964	5450	1661	1	2	4,000	T	2,000
	THIMBLE SHOAL CHANNEL. Under south ship channel; Chesapeake Bay	Chesapeake Bay Brdge. & Tun. Dist.	1964	5738	1749	1	2	4,000	T	2,000
	EAST RIVER MOUNTAIN. I-77 under East River Mt. on Va.-W. Va. border	Va. Dept. of Highways & Transp.	1974	5400	1646	2	2		T	
	MARYS ROCK. Mile 32 of Skyline Drive, Shenandoah Nat'l Park			660		1	2		U	
Wash.	BATTERY ST. Beneath Battery Street betw. 1st & 7th Aves.; Seattle	Wash. Dept. of Highways	1954	2140	652	2	2	23,500	T	5,875
	MT. BAKER RIDGE. U.S. 10 in Seattle		1940	1466		2	2			
W. Va.	WHEELING. I-70; Wheeling	W. Va. Dept. of Highways	1966	1490	454	2	2	29,000	L	7,250
	MEMORIAL. West Virginia.Turnpike; Kanawha County	W. Va. Turnpike Commission	1954	2669	814	1	2		T	
	BLAND CO. I-77			5661						
Wyo.	GREEN RIVER. I-80		1966	1135		2	2			

APPENDIX C

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